DESIGN AND ANALYSIS OF TWO PORT MIMO ANTENNAS WITH WIDEBAND ISOLATION

A Thesis submitted in partial fulfillment of the

Requirements for the degree of

MASTER OF TECHNOLOGY

IN

COMMUNCATION AND SIGNAL PROCESSING

BY

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UNDER THE GUIDANCE OF

PROF. S K BEHERA

Department of Electronics and Communication Engineering

National Institute of Technology Rourkela-769008

2013

Dedicated to My Family

Department of Electronics & Communication Engineering

National Institute of Technology Rourkela

Date: 28-05-2013

CERTIFICATE

This is to certify that the thesis entitled, "**Design and Analysis of two port MIMO antennas with wideband isolation**" submitted by Mr.**Manuel Prasanna.K** in partial fulfillment of the requirements for the award of Master of Technology Degree in Electronics and Communication Engineering with specialization in "**Communication and Signal Processing**" during the session 2012-2013 at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

S.K.BEHERA

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Manuel Prasanna.K

ABSTRACT

Ultrawideband (UWB) technology has rapidly gained popularity and demand for recent wireless communication systems after the allocation of 3.1- 10.6 GHz by the Federal Communications Commission (FCC) for UWB applications. Since then, a myriad of research opportunities and challenges exist for the design of UWB antenna systems for application in high speed wireless devices. Multiple-Input-Multiple-Output (MIMO) systems provide a significant increase in channel capacity without the need of additional bandwidth or transmit power by deploying multiple antennas for transmission to achieve an array gain and diversity gain, thereby improving the spectral efficiency and reliability. Since MIMO systems employ multiple antennas, they require high decoupling between antenna elements. Overall UWB MIMO systems require a high isolation of less than -16 dB and also a compact size for compatibility with integrated circuits. This thesis focuses on the analysis and design of MIMO antennas with a compact planar profile that have an operating range in the entire UWB (3.1- 10.6 GHz) and desired antenna performance characteristics.

This dissertation presents the work on the design of two- element MIMO antennas and various isolation structures and mechanisms to reduce the mutual coupling between the two elements, out of which two major antenna designs are proposed and analyzed separately for their isolation, bandwidth and radiation characteristics. First, a printed ultra wideband (UWB) MIMO antenna system is proposed for portable UWB applications. The MIMO antenna system consists of two semicircular radiating elements on a single low-cost FR4 substrate of a compact size of 35 mm × 40 mm and is fed by a 50-Ω microstrip line. A T- shaped slot is etched on the radiating elements to enhance the impedance bandwidth. The proposed antenna system operates over a wide frequency range from 4.4 to 10.7 GHz . A fork-shaped structure is introduced in the ground plane to increase the isolation between the antennas. Simulated results of S-parameters of the proposed antenna system are obtained and a high isolation of -20 dB is achieved in most of the band, which is found suitable for MIMO applications. The second antenna consists of a compact planar MIMO antenna system of size 36 mm × 40 mm with two hexagonal monopole elements. The impedance bandwidth and isolation are enhanced by a hexagonal shaped Defected Ground Structure (DGS). Simulated results show that the MIMO antenna with DGS has 10-dB return

loss from 4.4 GHz to 9.57 GHz, yielding 75% improvement in impedance bandwidth over that of the traditional MIMO antenna system without DGS. Isolation also is enhanced by the DGS. S_{21} results show that isolation exceeds 15 dB within the required band and 20 dB in most of the band.

Both MIMO antenna systems have a significant operating bandwidth covering almost the entire UWB and together with the proposed isolation structures are able to achieve isolation more than -16 dB.

CONTENTS

ABBREVIATIONS

UWB	**U**ltra Wide Band
FCC	Federal Communications Commission
MIMO	Multiple-Input-Multiple-Output
DGS	Defected Ground Structure
EBG	Electromagnetic Band Gap
MICs	Microwave Integrated Circuits
BW	Band Width
ABW	Absolute Band Width
FBW	Fractional Band Width
VSWR	Voltage Standing Wave Ratio
SWR	Standing Wave Ratio
MoM	Method of Moments
ITU-R	International Telecommunication Union- Radio communication
PSD	Power Spectral Density
GPS	Global Positioning System
LPI	Low Probability of Intercept
RF	Radio Frequency
PAN	Personal Area Networks
WPAN	Wireless Personal Area Networks
WUSB	Wireless Universal Serial Bus
WLANs	Wireless Local Area Networks
SD	Spatial Diversity
SM	Spatial Multiplexing

AAS	Adaptive Antenna Systems
SNR	Signal to Noise Ratio
SIR	Signal to Interference Ratio
SISO	Single-Input Single-Output
SIMO	Single-Input Multiple-Output
MISO	Multiple-Input Single-Output
OFDMA	Orthogonal Frequency Division Multiple Access
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
PIFAs	Planar Inverted –F Antennas

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Chapter 1

Introduction

The use of wireless devices is the latest trend in communication technology, and there is a constant demand for compactness or miniaturization of wireless electronic devices, as well as an increase in speed and data rate for these devices. In this regard, UWB MIMO antenna systems are being considered for better performance, and they present antenna engineers with many design challenges.

1.1 Motivation for UWB MIMO Antenna Design:

The potential of UWB technology is enormous owing to its tremendous advantages such as the capability of providing high speed data rates at short transmission distances with low power dissipation. The rapid growth in wireless communication systems has made UWB an outstanding technology to replace the conventional wireless technologies in today's use like Bluetooth and wireless LANs, etc. A lot of research has been done to develop UWB LNAs, mixers and entire front-ends but not that much to develop UWB antennas. Recently, academic and industrial communities have realized the tradeoffs between antenna design and transceiver complexity. In general, the transceiver complexity has been increased, with the introduction of advanced wireless transmission techniques. In order to enhance the performance of transceiver without sacrificing its costly architecture, advanced antenna design should be used as the antenna is an integral part of the transceiver. Also ,the complexity of the overall transceiver is reduced [1].

To implement UWB technology, there are many challenges to overcome. UWB has a significant effect on antenna design. It has attracted a surge of interest in antenna design by providing new challenges and opportunities for antenna designers as UWB systems require an antenna with an operating bandwidth covering the entire UWB (3.1- 10.6 GHz) and capable of receiving on associated frequencies at the same time [2]. Consequently, the antenna behavior and performance have to be consistent and predictable across the UWB. Moreover, UWB is a technology that modulates impulse based waveforms rather than continuous carrier waves. Hence, the design of UWB antennas requires different considerations from those used in designing narrowband antennas. The hardest challenge in designing a UWB antenna is to attain wide impedance bandwidth with high radiation efficiency. UWB antennas achieve a bandwidth, greater than 100% of the center frequency to ensure sufficient impedance so that only less than 10 % of incident signal is lost due to reflections at the antenna's input terminal [2]. A return loss of greater than 10 dB is necessary in order to obtain high radiation efficiency. It is required as UWB transmission is of very low power (below the noise floor level) and with high sensitivity [1].

The concurrent surge of wireless devices, with high level of miniaturization and high frequency of operation, has enhanced the interest in designing high performance antenna types. Therefore, there is a growing demand for small and low cost UWB antennas that are able to provide satisfactory performance in both time and frequency domains. The trend in recent wireless systems, including UWB based systems, are to build small, low-profile integrated circuits so as to be compatible with portable wireless devices. Also, the size affects the gain and bandwidth. Therefore, the size of the antenna is considered as one of the critical issues in UWB system design. The use of a planar design can minimize the volume of the UWB antennas by replacing three-dimensional radiators with their planar versions. Also, the two-dimensional (2D) geometry makes the fabrication easier. As a result, the planar antenna can be printed on a PCB and thus can be easily integrated into RF circuits [3].

Recently, there is a demand to increase the data rate of existing wireless communication systems. The application of diversity techniques, most commonly assuming two antennas in a mobile terminal, can enhance the data rate and reliability without sacrificing additional spectrum or transmitted power in rich scattering environments. MULTIPLE-INPUT-MULTIPLE-OUTPUT (MIMO) technology has attracted attention in modern wireless communication systems Multiple-input-multiple-output (MIMO) systems transmit the same power using multiple antennas at the transmitter and receiver thereby increasing the channel capacity without the need of additional bandwidth or power.. MIMO UWB systems can further increase the channel capacity as compared to conventional MIMO systems for narrowband applications. To combat the multipath fading problem in an indoor UWB wireless communication system, an UWB diversity antenna system is a promising candidate. However, for an efficient MIMO antenna system mutual coupling between the individual antennas should be as low as possible.

Hence, these design challenges and features for achieving high channel capacity with less complexity kindles the interest and serves as a motivation to the researchers in the study and design of MIMO antennas for high data rate UWB applications.

1.2 Background:

Ultra-wideband (UWB) technology is certainly not a new concept, though it may have a revolutionary approach to development and application in wireless communication devices. The concept of Ultrawideband technology started in the early 1960's, where research in time-domain electromagnetics lead to the application of impulse measurement techniques in the design of wideband antennas. This paved the way to the development of short pulse radar systems. UWB was also referred to as 'baseband' or 'impulse' technology. Later, through advances in this technology, many techniques and implementation methods had been developed for a variety of applications like radar, positioning systems and short distance indoor applications, etc.

Multiple-Input-Multiple-Output or MIMO is one of the latest forms of smart antenna technology to improve communication performance. The concept of spatial multiplexing using MIMO was first introduced in 1993. In the commercial area, the first system was developed in 2001, where MIMO was used with orthogonal frequency-division multiple access technology (MIMO-OFDMA), which supported both diversity coding and spatial multiplexing.

The introduction of MIMO technology proved to be one of the best techniques to enhance the channel capacity within the available bandwidth and power.

Recently, microstrip antenna designers also employ MIMO technology, where they use two or more radiating patches in the design for transmission. In the past decade, several MIMO/ Diversity antennas have been proposed that exist in the literature, out of which a few are designed to operate in the frequency range of 3.1 to 10.6 GHz, suitable for UWB applications.

Several studies have been carried out on various MIMO antenna systems with two and four radiating elements and various methods are proposed to improve the isolation between the antenna elements. Various structures like the mushroom–shaped EBG structures [4]–[5], defected ground plane structures [6]–[7] have been proposed to reduce the mutual coupling by suppressing the ground current flowing between the radiating elements. In [8], a two – port compact UWB MIMO antenna for USB Dongle applications is proposed in which isolation of -26 dB is achieved by a slot formed between the monopole and the ground plane. The impedance bandwidth is from 3.1 to 5.15 GHz. In another UWB Diversity antenna [9], isolation of < -20 dB is achieved by optimizing the shape of the ground plane and through slots in the radiating elements. The operating frequency range of the proposed antenna is 3.1–5 GHz. However, both of these antennas [8] and [9] can cover only the lower UWB band. In [10], a diversity antenna covering the entire UWB has been designed, in which stubs are introduced to reduce the mutual coupling. In [10], enhanced isolation is obtained at the cost of increased complexity and size of the overall antenna system.

1.3 Contributions:

The novel contributions to this thesis are as follows:

- Considering the existing designs and challenges in UWB MIMO antennas, various isolation structures and mechanisms are proposed to enhance isolation and bandwidth.
- A novel compact two-port UWB MIMO antenna system with high isolation using a Fork-Shaped structure has been designed and analyzed
- A hexagonal MIMO antenna system with Defected Ground Structure (DGS) to enhance bandwidth and isolation has also been designed and analyzed**.**

1.4 Thesis Organization:

The remaining part of this thesis is organized as follows:

Chapter 2 reviews the basic theory of microstrip antennas and their types, feeding methods and design procedure of basic microstrip patches. Brief descriptions of basic antenna parameters and model analysis of microstrip antennas are also provided in this chapter.

Chapter 3 presents a brief introduction to UWB and multiple antenna techniques for increased channel capacity. The concepts of MMO channel model and capacity are reviewed. Design challenges n UWB MIMO antenna systems are presented and existing systems are studied.

Chapter 4 & 5 proposes two MIMO antenna systems with different ground plane structures to provide wideband isolation. Simulation results are shown and analyzed for antenna performance characteristics.

Chapter 6 offers conclusions and guidelines for future research.

Chapter 2

Theory of Microstrip Antennas

2.1 Introduction to microstrip patch antennas:

The Microstrip patch antenna has a dielectric substrate with a radiating patch and the feed lines are etched on one side and a ground plane on the other side as shown in Figure (2.1). The shape of the patch is not constrained (could be square, rectangular, circular, triangular or elliptical) and it is generally made of conducting material such as copper or gold.

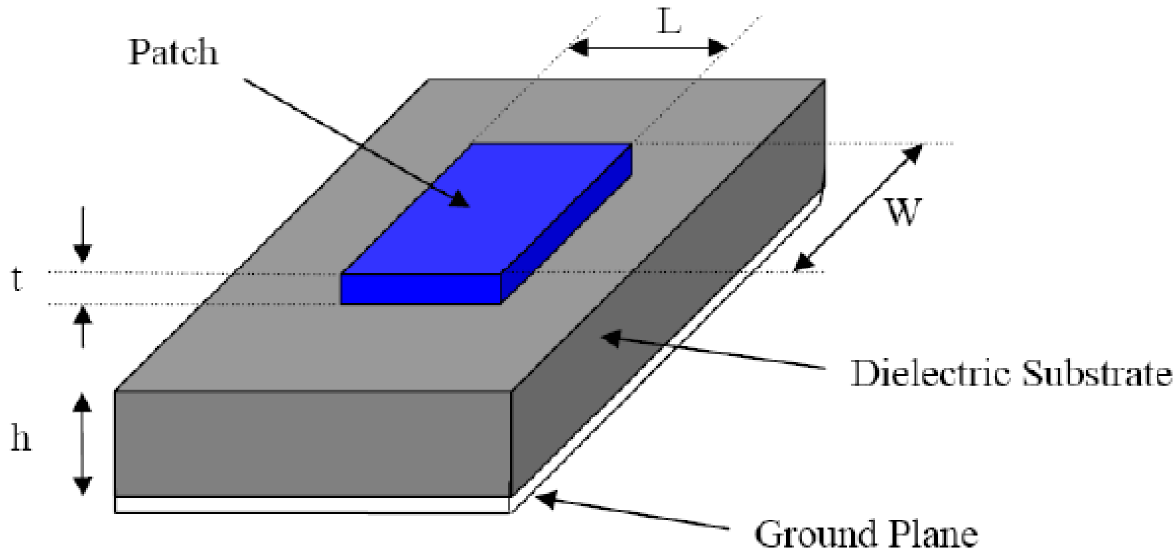


Fig. 2.1 Microstrip patch antenna

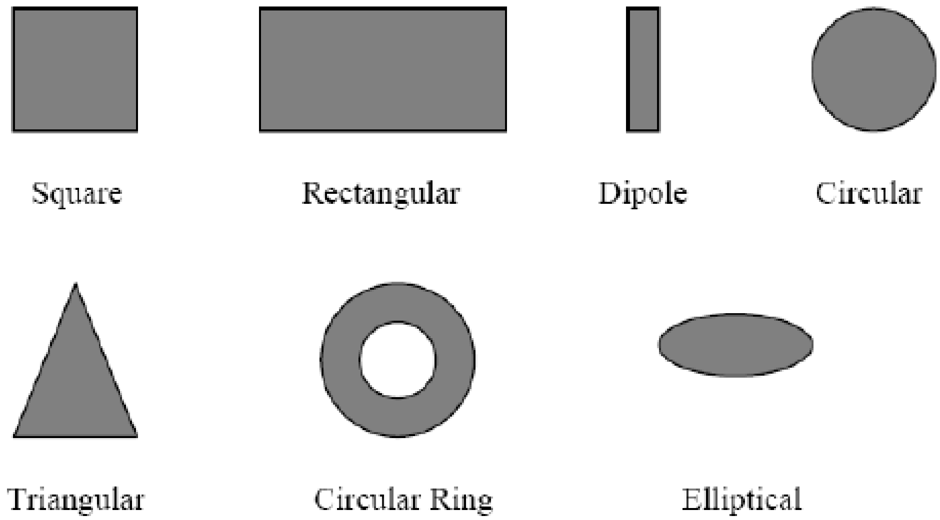


Fig. 2.2 Some common shapes of microstrip patches

The fringing fields between the patch edge and the ground plane cause the microstrip patch antennas to radiate. A better performance in the antenna calls for a thick dielectric substrate having low dielectric constant which provides better efficiency, larger bandwidth and better radiation [11]. However, such a configuration results in large size of antenna. The design of a compact microstrip patch antenna demands higher dielectric constants, which are less efficient and result in narrower bandwidth. Therefore an optimization is to be achieved between antenna dimensions and antenna performance.

2.2 Feeding Techniques:

The methods by which microstrip patch antennas are fed can be classified into two categories, namely contacting and non-contacting. In the first method, the RF power is directly fed to the radiating patch using a connecting element such as a microstrip line. In the latter method, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch [11]. The most popular feed techniques used are the microstrip line, coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes).

The methods by which power is coupled in or out of an antenna are broadly classified as contacting and non-contacting. Contacting feeds imply direct connection of transmission lines (coax or microstrip) to the patch antenna. The location of connection within the patch boundaries determines the input impedance. In the case of non-contacting feeds electromagnetic fields coupling are used to transfer the power between feed lines and the radiating patch. Though the design of non-contacting feed is difficult, the degree of freedom is more than that of contacting feed.

2.2.1 Microstrip Line Feed:

Here a conducting strip, which is smaller in width as compared to the microstrip patch, is connected directly to the edge of the patch as shown in Figure (2.3). The major advantage is that the feed can be etched on the same substrate to provide a planar structure

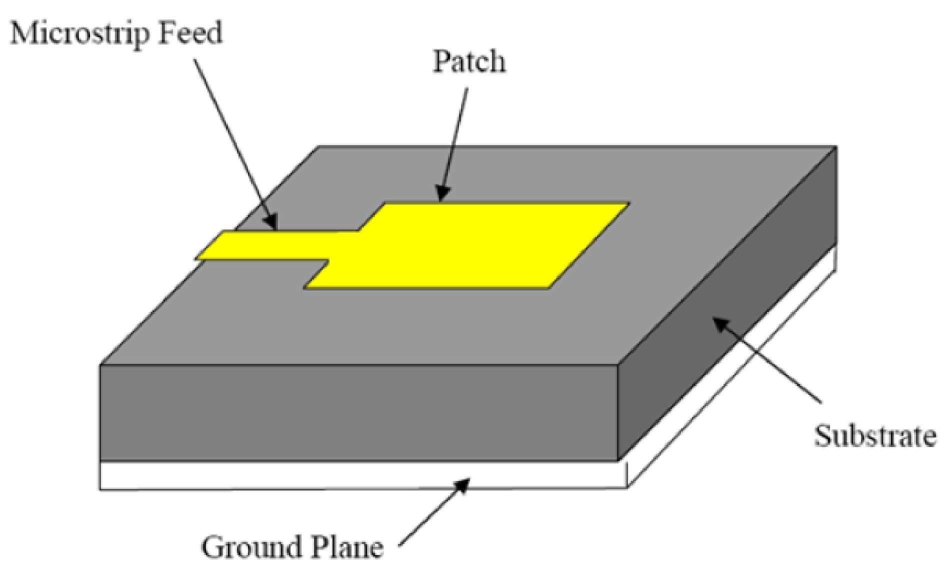


Fig. 2.3 Microstrip line feed.

The thickness of the dielectric substrate being used increases surface waves and spurious feed radiation which hampers the bandwidth of the antenna [11]. The feed radiation also results in undesired cross polarized radiation.

2.2.2 Coaxial Probe Feed:

A common technique used for feeding Microstrip patch antennas is coaxial feed or probe feed. The outer conductor of the coaxial connector is connected to the ground plane and the inner conductor is extended through the dielectric and is soldered to the radiating patch.

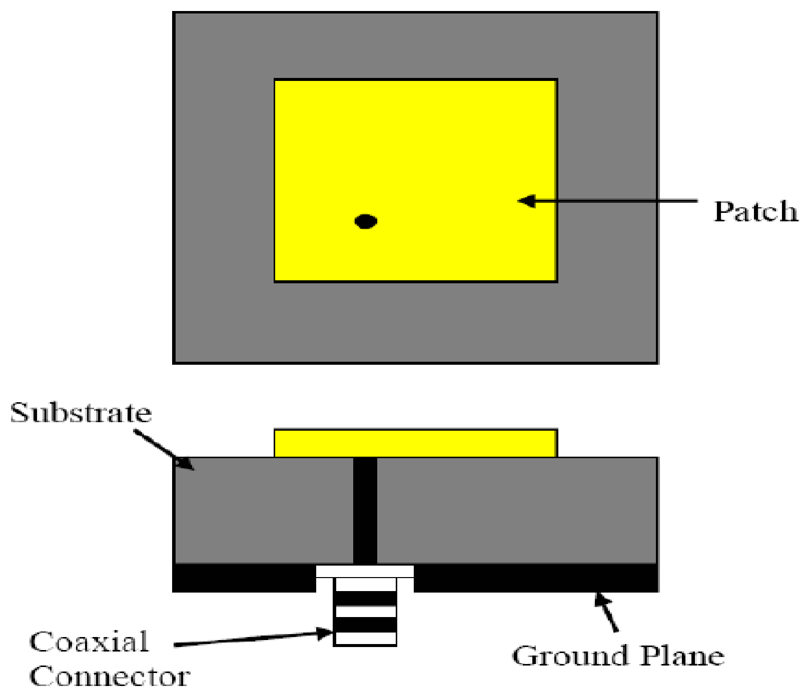


Fig. 2.4 Probe- fed rectangular patch antenna.

The feed can be placed at any desired location inside the patch in order to match with its input impedance. Hence this method is advantageous and it is also easy to fabricate and has low spurious radiation. However, its major disadvantage is that it provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate and the connector protrudes outside the ground plane, thus not making it completely planar for thick substrates ($h > 0.02\lambda_0$). Also, for thicker substrates matching problems arise due to increased probe length which makes the input impedance more inductive. Therefore the Microstrip line feed and the coaxial feed is not suitable for a thick dielectric substrate, which provides broad bandwidth.

The following non-contacting feed technique is more advantageous.

2.2.3 Aperture Coupled Feed:

Here a ground plane as shown in Figure (2.5) separates the radiating patch and the microstrip feed line and the coupling between both of them is made through a slot or an aperture in the ground plane.

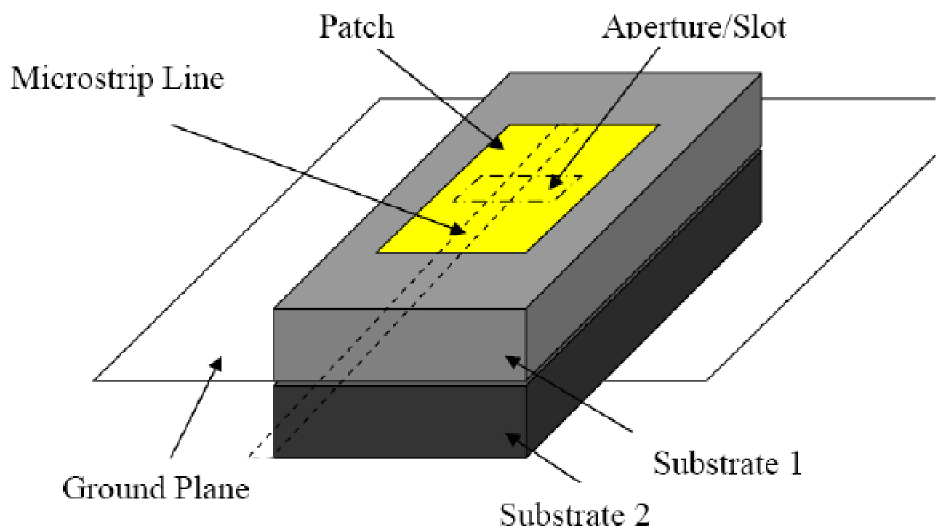


Fig. 2.5 Aperture coupled feed.

The coupling aperture is usually centred under the patch as the symmetry in the configuration results in lower cross-polarization. The location of the aperture along with the shape and size determines the amount of coupling from the feed line to the patch. The ground plane which separates the patch and the feed line reduce the spurious radiation. Usually, a high dielectric material is used for the bottom substrate and a thick, low dielectric constant material is used for the top substrate to optimize radiation from the patch [12].

In addition to increasing the antenna thickness the multiple layers are also difficult to fabricate. This feeding scheme also provides narrow bandwidth.

2.2.4 Proximity Coupled Feed:

This type of feed technique is also called as the electromagnetic coupling scheme [13]. As shown in Figure (3-9), two dielectric substrates are used such that the feed line is between the two substrates and the radiating patch is on top of the upper substrate. The main advantage of this feed technique is that it eliminates spurious feed radiation and provides very high bandwidth (as high as 13%) [11], due to overall increase in the thickness of the microstrip patch antenna. This scheme also provides choices between two different dielectric media, one for the patch and one for the feed line to optimize the individual performances.

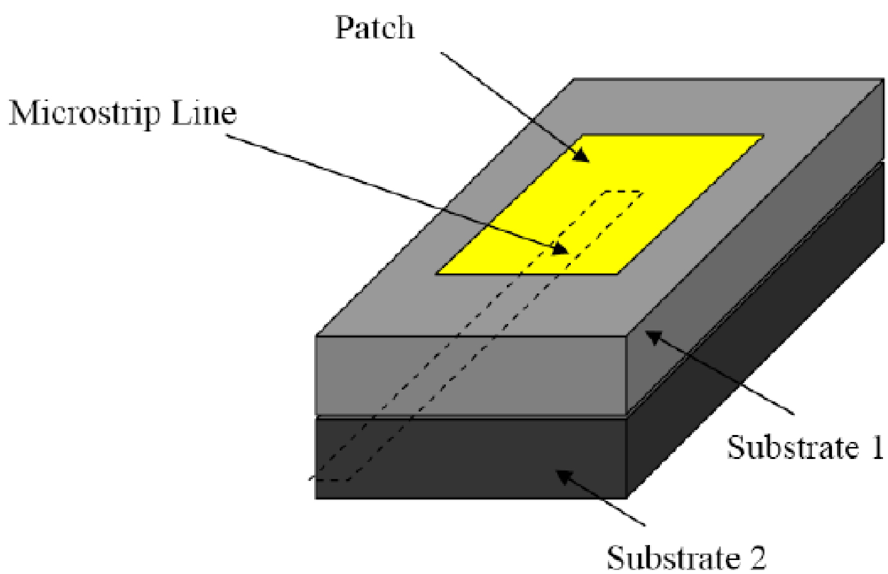


Fig. 2.6 Proximity coupled feed.

Matching can be achieved by controlling the length of the feed line and the width-to-line ratio of the patch. The major disadvantage of this feed scheme is that it is difficult to fabricate because of the two dielectric layers which need proper alignment. Also, there is an increase in the overall thickness of the antenna.

Table (2-1) below summarizes the characteristics of the different feed techniques.

Table 2-1 : Comparision of different feed techniques.

Feed type / property	Microstrip Line Feed	Coaxial Feed	Aperture Coupled Feed	Proximity Coupled Feed
Spurious feed radiation	More	More	Less	Minimum
Reliability	Better	Poor due to soldering	Good	Good
Ease of fabrication	Easy	Soldering and drilling needed	Alignment required	Alignment required
Impedance Matching	Easy	Easy	Easy	Easy
Bandwidth (achieved with impedance matching)	2-5%	2-5%	2-5%	13%

2.3 Advantages and Limitations of Microstrip Antennas:

Microstrip antennas have many advantages compared to conventional microwave antennas which are listed as follows:

- Light weight and low volume.
- Low profile planar configuration which can be easily made conformal to host surface.
- Low fabrication cost, hence can be manufactured in large quantities.
- Supports both, linear as well as circular polarization.
- Can be easily integrated with microwave integrated circuits (MICs).
- Capable of dual and triple frequency operations.
- Mechanically robust when mounted on rigid surfaces.

However, microstrip antennas have the following limitations when compared with microwave antennas:

- Narrow bandwidth
- Low efficiency and gain
- Extraneous radiation from feeds and junctions.
- Poor end fire radiator except tapered slot antennas.
- Low power handling capacity.
- Surface wave excitation.

2.4 Applications:

Microstrip antennas were initially used in military systems and satellites. Recently, these antennas are being used for commercial applications due to reduced cost. Some of the applications are listed below:

- Environmental instrumentation and remote sensing.
- Biomedical radiator
- Mobile communication handsets and base stations.
- Satellite communications.
- Commercial aircraft and missiles.

- Satellite navigation receivers.
- Integrated antennas.

2.5 Fundamental Antenna Parameters:

To describe the performance of an antenna, definitions of various parameters are necessary. In practice, there are several commonly used antenna parameters, including bandwidth, radiation pattern, directivity, gain, input impedance, and so on.

2.5.1 Bandwidth:

Bandwidth (*BW*) is the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard. The bandwidth can be considered to be the range of frequencies, on either side of the center frequency, where the antenna characteristics are within an acceptable value of those at the center frequency. Generally, in wireless communications, the antenna is required to provide a return loss less than -10dB over its frequency bandwidth.

The frequency bandwidth of an antenna can be expressed as either absolute band-width (*ABW*) or fractional bandwidth (*FBW*). If f_H and f_L denote the upper edge and the lower edge of the antenna bandwidth, respectively. The *ABW* is defined as the difference of the two edges and the *FBW* is designated as the percentage of the frequency difference over the center frequency, as given in Equation (2-1) and (2-2), respectively.

$$\mathrm{ABW} = f_H - f_L \tag{2-1}$$

$$\mathrm{FBW} = 2\frac{f_H - f_L}{f_L + f_L} \tag{2-2}$$

For broadband antennas, the bandwidth can also be expressed as the ratio of the upper to the lower frequencies, where the antenna performance is acceptable, as shown in Equation (2-3).

$$\mathrm{BW} = \frac{f_H}{f_L} \tag{2-3}$$

2.5.2 Radiation Pattern:

The radiation pattern (or antenna pattern) is the representation of the radiation properties of the antenna as a function of space coordinates. In most cases, it is determined in the far-field region where the spatial (angular) distribution of the radiated power does not depend on the distance. Usually, the pattern describes the normalized field (power) values with respect to the maximum values.

The radiation property of most concern is the two- or three-dimensional (2D or 3D) spatial distribution of radiated energy as a function of the observer's position along a path or surface of constant radius. In practice, the three-dimensional pattern is sometimes required and can be constructed in a series of two-dimensional patterns. For most practical applications, a few plots of the pattern as a function of φ for some particular values of frequency, plus a few plots as a function of frequency for some particular values of θ will provide most of the useful information needed, where φ and θ are the two axes in a spherical coordinate system. .

For a linearly polarized antenna, its performance is often described in terms of its principle *E* plane and *H*-plane patterns. The *E*-plane is defined as the plane containing the electric-field vector and the direction of maximum radiation whilst the *H*-plane is defined as the plane containing the magnetic-field vector and the direction of maximum radiation [14].

There are three common radiation patterns that are used to describe an antenna's radiation property:

- **Isotropic:** A hypothetical lossless antenna having equal radiation in all directions. It is only applicable for an ideal antenna and is often taken as a reference for expressing the directive properties of actual antennas.
- **Directional:** An antenna having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. This is usually applicable to an antenna where its maximum directivity is significantly greater than that of a half- wave dipole.

- **Omni-Directional:** An antenna having an essentially non-directional pattern in a given plane and a directional pattern in any orthogonal plane.

2.5.3 Directivity:

To describe the directional properties of antenna radiation pattern, directivity *D* is introduced and it is defined as the ratio of the radiation intensity *U* in a given direction from the antenna over that of an isotropic source. For an isotropic source, the radiation intensity U_0 is equal to the total radiated power P_{rad} divided by 4π. So the directivity can be calculated by:

$$\mathrm{D} = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} \tag{2-4}$$

If not specified, antenna directivity implies its maximum value, i.e. D_0.

$$D_0 = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}} \tag{2-5}$$

2.5.4 Gain:

The antenna absolute gain according to [15] is defines as "the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically."

Antenna gain *G* is closely related to the directivity, but it takes into account the radiation efficiency e_{rad} of the antenna as well as its directional properties, as given by:

$$G = e_{rad}\, D \tag{2-6}$$

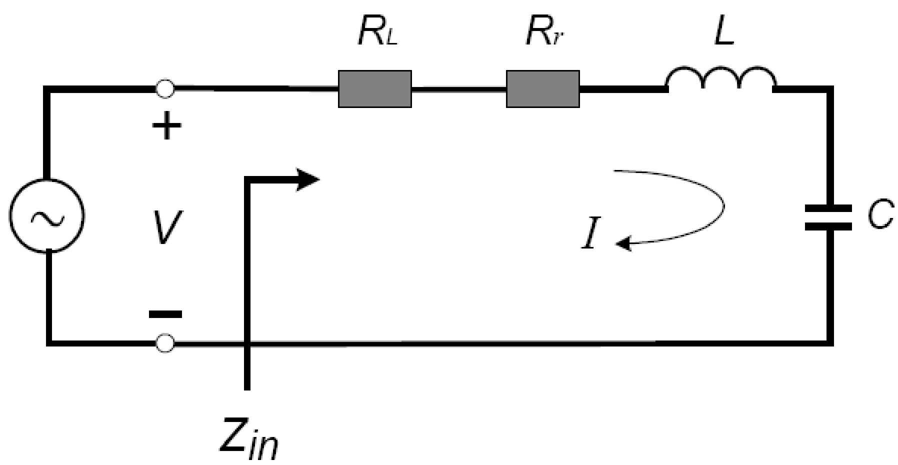


Fig. 2.7 Equivalent circuit of an antenna.

Figure 2.7 shows the equivalent circuit of the antenna, where R_r, R_L, L and C represent the radiation resistance, loss resistance, inductor and capacitor, respectively. The radiation efficiency e_{rad} is defined as the ratio of the power delivered to the radiation resistance to the power delivered to R_r and R_L. So the radiation efficiency can be written as:

$$e_{rad} = \frac{\frac{1}{2}|I|^2 R_r}{\frac{1}{2}|I|^2 R_r + \frac{1}{2}|I|^2 R_L} = \frac{R_r}{R_r + R_L} \qquad (2\text{-}7)$$

Similarly, the maximum gain G_0 is related the maximum directivity D_0 by:

$$G_0 = e_{rad} D_0 \qquad (2\text{-}8)$$

2.5.5 VSWR:

VSWR stands for **Voltage Standing Wave Ratio**, and is also referred to as Standing Wave Ratio (SWR). VSWR is a function of the reflection coefficient, which describes the power reflected from the antenna. If the reflection coefficient is given by Γ, then VSWR is defined as:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{2-9}$$

The VSWR is always a real and positive number for antennas. The smaller the VSWR is, the better the antenna is matched to the transmission line and the more power is delivered to the antenna. The minimum VSWR is 1.0. In this case, no power is reflected from the antenna, which is ideal.

Often antennas must satisfy a bandwidth requirement that is given in terms of VSWR. For instance, an antenna might claim to operate from 100-200 MHz with VSWR<3. This implies that the VSWR is less than 3.0 over the specified frequency range. This VSWR specification also implies that the reflection coefficient is less than 0.5 over the quoted frequency range.

2.5.6 Impedance Bandwidth:

Impedance bandwidth indicates the bandwidth for which the antenna is sufficiently matched to its input transmission line such that 10% or less of the incident signal is lost due to reflections. Impedance bandwidth measurements include the characterization of the VSWR and return loss throughout the band of interest.

2.5.7 Polarization:

Antenna polarization indicates the polarization of the radiated wave of the antenna in the far-field region. The polarization of a radiated wave is the property of an electromagnetic wave describing the time varying direction and relative magnitude of the electric-field vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation. Typically, this is measured in the direction of maximum radiation. There are three classifications of antenna polarization: linear, circular and elliptical. Circular and linear polarizations are special cases of elliptical polarization. Typically, antennas will exhibit elliptical polarization to some extent. Polarization is indicated by the electric field vector of an antenna oriented in space as a function of time. Should the vector follow a line, the wave is linearly polarized. If it follows a circle, it is circularly polarized (either with a left hand sense or right hand sense). Any other orientation is said to represent an elliptically polarized wave.

2.6 Model Analysis of Microstrip Antennas:

The most widely used microstrip patch configuration is the rectangular patch. Analysis of this patch is easy using transmission-line and cavity models. The transmission-line model is the easiest of all and yields accurate results.

2.6.1 Transmission-Line Model:

This model represents the microstrip antenna by two slots separated by a transmission line of length *L*. Fringing effects occur at the edges of the patch and is a function of *L*, width *W* of the patch and height *h* of the substrate.

Due to fringing effects, the length of the patch is extended on the ends by a distance ΔL, which is a function of the effective dielectric constant ϵ_{reff} and width-to-height ratio. The approximate relation for extended length is given by:

$$\frac{\Delta L}{h} = 0.412\ \frac{\left(\epsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\epsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \qquad (2\text{-}10)$$

Where ϵ_{reff} is given by:

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\,\frac{h}{W}\right]^{-1/2} \qquad (2\text{-}11)$$

Hence, the effective length of the patch is

$$L_{\mathrm{eff}} = L + 2\Delta L \qquad (2\text{-}12)$$

The resonant frequency of the microstrip antenna is related to its length as:

$$(f_r)_{010} = \frac{1}{2L\sqrt{\epsilon_r}\sqrt{\mu_0\epsilon_0}} = \frac{v_0}{2L\sqrt{\epsilon_r}} \tag{2-13}$$

2.6.2 Practical Design Procedure:

For a specified dielectric constant of the substrate ϵ_r, resonant frequency f_r and height of the substrate h, the following design equations are used to calculate the length and width of the patch:

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \tag{2-14}$$

where v_0 is the free-space velocity of light.

Now, the extended length ΔL can be calculated using equation (2-10).

The actual length of the patch can be determined using

$$L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L \tag{2-15}$$

2.7 Full wave solutions – Method Of Moments (MoM):

The method of moments provides the full wave analysis for the microstrip patch antenna. In this method, the surface currents are used to model the microstrip patch and the volume polarization currents are used to model the fields in the dielectric slab. It has been shown by Newman and Tulyathan [16] how an integral equation is obtained for these unknown currents and using the Method of Moments, these electric field integral equations are converted into matrix equations which can then be solved by various techniques of algebra to provide the result. A brief overview of the Moment Method described [16] is given below.

The basic form of the equation to be solved by the Method of Moment is

$$F(g) = h. \tag{2-16}$$

where F is a known linear operator, g is an unknown function, and h is the source or excitation function. The aim here is to find g ,when F and h are known. The unknown function g can be expanded as a linear combination of N terms to give:

$$g = \sum_{n=1}^{N} a_n g_n = a_1 g_1 + a_2 g_2 + \ldots.. + a_N g_N \tag{2-17}$$

Where a_n is an unknown constant and g_n is a known function usually called a basis or expansion function. Substituting equation (2-16) in (2-17) and using the linearity property of the operator F, we can write:

$$\sum_{n=1}^{N} a_n F(g_n) \tag{2-18}$$

The basic functions g_n must be selected in such a way, that each $F(g_n)$ in the above equation can be calculated. The unknown constants a_n cannot be determined directly because there are N unknowns, but only one equation. One method of finding these constants is the method of weighted residuals. In this method, a set of trial solutions is established with one or more variable parameters. The residuals are a measure of the difference between the trial solution and the true solution. The variable parameters are selected in a way which guarantees a best fit of the trial functions based on the minimization of the residuals. This is done by defining a set of N weighting (or testing) functions $\{w_m\}$ w_1, w_2 ,..... w_n in the domain of the operator F. Taking the inner product of these functions, equation (2-18) becomes:

$$\sum_{n=1}^{N} a_n \langle w_m, F(g_n) \rangle = \langle w_m, h \rangle \tag{2-19}$$

Where m = 1,2,.....N

Writing in Matrix form, we get:

$$[F_{mn}]\,[a_n] \;=[h_m] \tag{2-20}$$

Where,

$$[F_{mn}] \;= \begin{bmatrix} \langle w_1, F(g_1)\rangle\langle w_1, F(g_2)\rangle \dots\dots \\ \langle w_2, F(g_1)\rangle\langle w_2, F(g_2)\rangle \dots\dots \\ \vdots \\ \vdots \end{bmatrix} \qquad [a_n] = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_N \end{bmatrix} \qquad [h_m] = \begin{bmatrix} \langle w_1, h\rangle \\ \langle w_2, h\rangle \\ \langle w_3, h\rangle \\ \vdots \\ \langle w_N, h\rangle \end{bmatrix}$$

The unknown constants a_n can now be found using algebraic techniques such as LU decomposition or Gaussian elimination. It must be remembered that the weighting functions must be selected appropriately so that elements of $\{w_n\}$ are not only linearly independent but they also minimize the computations required to evaluate the inner product. One such choice of the weighting functions may be to let the weighting and the basis function be the same, that is w_n=g_n, This is called as the Galerkin's Method as described by Kantorovich and Akilov [17]. From the antenna theory point of view, we can write the Electric field integral equation as:

$$\text{E}=f_e(J) \tag{2-21}$$

where E is the known incident electric field.

J is the unknown induced current.

f_e is the linear operator.

The first step in the moment method solution process would be to expand J as a finite sum of basis function given as:

$$\text{J}=\textstyle\sum_{i=1}^{M} J_i b_i \tag{2-22}$$

where b_i is the i[th] basis function and J_i is an unknown coefficient. The second step involves the defining of a set of M linearly independent weighting functions, w_j. Taking the inner product on both sides and substituting equation (2-21) in equation (2-22) we get:

$$\langle w_j, E \rangle = \sum_{i=1}^{M} \langle w_j, f_e(j_i, b_i) \rangle \tag{2-23}$$

where $j = 1,2,.....M$

Writing in Matrix form as,

$$\lfloor Z_{ij} \rfloor [J] = \lfloor E_j \rfloor \tag{2-24}$$

where $Z_{ij} = \langle w_j , f_e(b_i) \rangle$

$E_j = \langle w_j, E \rangle$

J is the current vector containing the unknown quantities.

The vector E contains the known incident field quantities and the terms of the Z matrix are functions of geometry. The unknown coefficients of the induced current are the terms of the J vector. Using any of the algebraic schemes mentioned earlier, these equations can be solved to give the current and then the other parameters such as the scattered electric and magnetic fields can be calculated directly from the induced currents. Thus, the Moment Method has been briefly explained for use in antenna problems.

Chapter 3

UWB MIMO Antenna Systems

3.1 Introduction to UWB:

Ultra-wideband (UWB) formerly known as '*pulse radio*' is a modern technology for transmitting information over a large bandwidth (> 500 MHz), promising high data rates with low power consumption. The unlicensed use of 3.1 -10.6 GHz has been authorized by the Federal Communications Commission for short distance high data rate indoor applications like PAN wireless connectivity. Recently, International Telecommunication Union Radiocommunication Sector (ITU-R) defined UWB as the transmission in which the bandwidth of the emitted signal exceeds the minimum of either 500 MHz or 20% of the center frequency, i.e. fractional bandwidth should be larger than 20% throughout the transmission. Fractional Bandwidth B_f is defined as the ratio of bandwidth at return loss(<-10 dB) to its center frequency.

$$B_f = \frac{BW}{f_c} \times 100\% = \frac{f_h - f_1}{\left(\frac{f_h + f_1}{2}\right)} \times 100\% = 2\,\frac{(f_h - f_1)}{(f_h + f_1)} \times 100\% \qquad (3\text{-}1)$$

f_h - upper cut-off frequency;

f_l - lower cut-off frequency;

Table 3-1 Classification of signals based on fractional bandwidth

Narrowband	$B_f < 1\%$
Wideband	$1\% < B_f < 20\%$
Ulrawideband	$B_f > 20\%$

Based on [18], UWB systems with center frequency above 2.5 GHz are required to have a -10 dB bandwidth of at least 500 MHz, whereas UWB systems with center frequency below 2.5 GHz should have a minimum fractional bandwidth of 0.2. The FCC has authorized that UWB transmission can operate in the range from 3.1 GHz to 10.6 GHz, with the power spectral density PSD) satisfying a specific spectral mask assigned by the FCC.

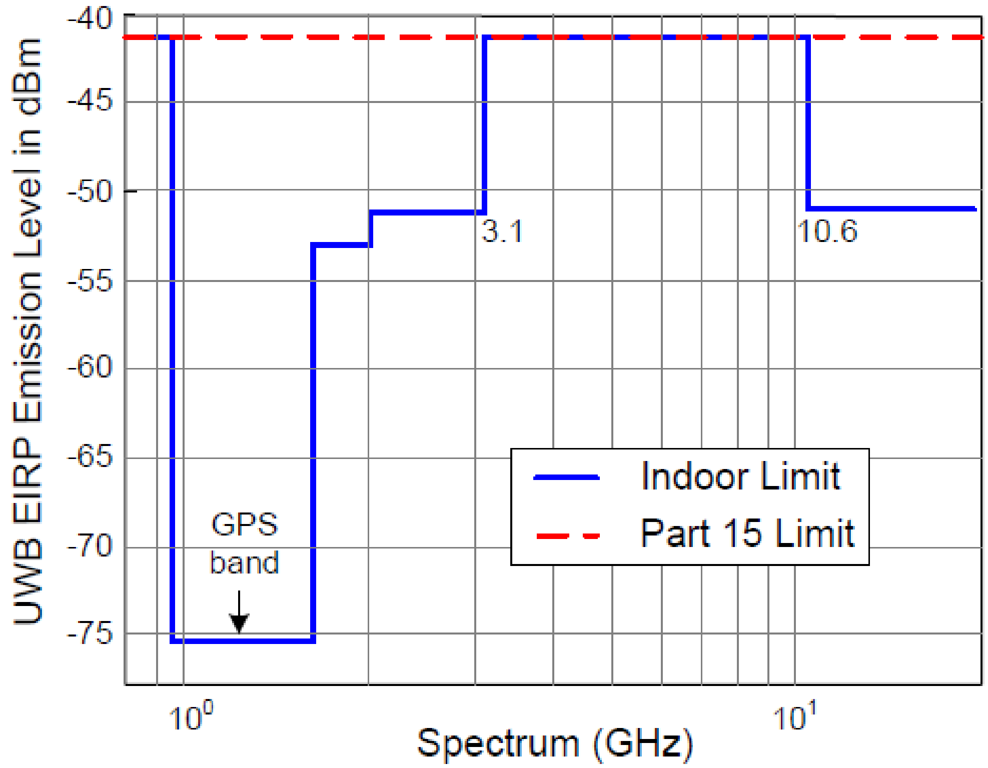


Fig 3.1 UWB spectral mask for indoor communication systems.

The above figure illustrates the spectral mask for indoor UWB systems. According to the spectral mask, the PSD of UWB signal measured in 1 MHz bandwidth must not exceed -41.3 dBm, which complies with the Part 15 general emission limits to successfully control radio interference. For particularly sensitive bands, such as the global positioning system (GPS) band (0.96 - 1.61 GHz), the PSD limit is much lower. As depicted in Fig.3.1, such ruling allows the UWB devices to overlay existing narrowband systems, while ensuring sufficient attenuation to limit adjacent channel interference. Although only the US permits operation of UWB devices currently, regulatory efforts are under way in many countries, especially in Europe and Japan [19]. Market drivers for UWB technology are many even at this early stage, and are expected to include new applications in the next few years.

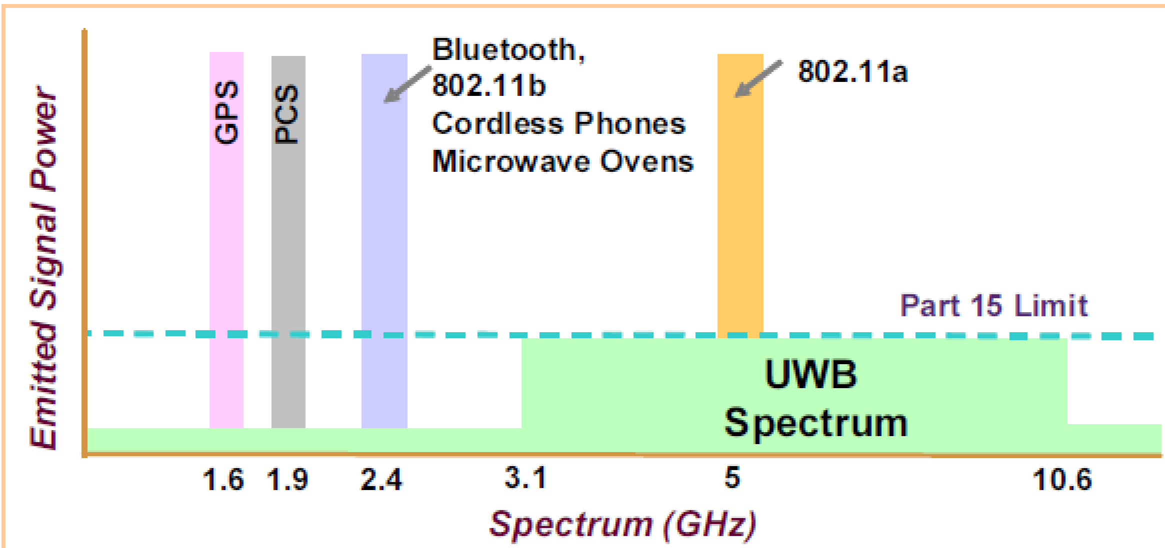


Fig 3.2 UWB spectrum allocation.

3.1.1 UWB Advantages:

Due to the ultra-wideband nature, UWB systems come with unique benefits that have been attractive for the radar and communications applications. The key advantages of UWB can be summarized as [20]

1) Extremely high data rates possible
   - Speeds up to 500 Mbps can be achieved under current regulations.

2) Potential for high capacity
   - Can achieve high throughput.

3) Low transmission power and low cost
   - Can directly modulate a baseband pulse
   - Extremely low transmission energy (less than 1mW).

4) Extensive multipath diversity

5) High precision ranging and localization at the centimeter level.

6) Highly flexible
   - Can dynamically trade-off throughput for distance.

The extremely large bandwidth occupied by UWB gives the potential of very high theoretical capacity, yielding very high data rates. This can be seen by considering Shannon's capacity equation [21],

$$C= B\, log_2\left(1+\frac{S}{N}\right) \qquad (3\text{-}2)$$

where C is the maximum channel capacity, B is the signal bandwidth, S is the signal power, and N is the noise power. The Shannon's equation shows that the capacity can be improve by increasing the signal bandwidth or by increasing the signal power. Moreover, it shows that increasing channel capacity requires linear increases in bandwidth while similar channel capacity increases would require exponential increases in power. Thus, from Shannon's equation we can see that UWB system has a great potential for high speed wireless communications.

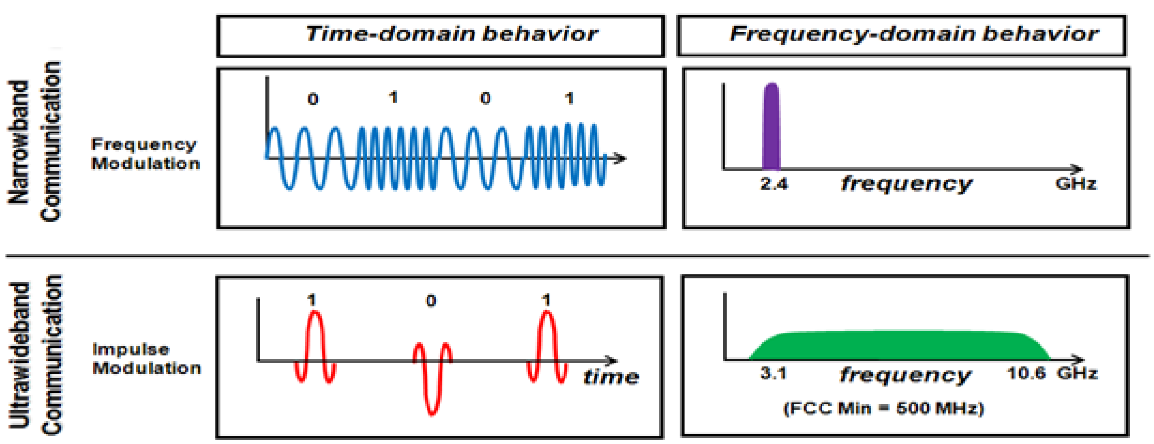


Fig 3.3 Comparison of UWB and narrowband modulation schemes

Moreover, UWB is a technology that modulates impulse based waveforms rather than continuous carrier waves thereby having several advantages over conventional narrowband systems.

- Low power spectral density allows coexistence with existing users and has a Low Probability of Intercept (LPI).
- Data rate may be traded for power spectral density and multipath performance.
- Large bandwidth enables fine time resolution for network time distribution, precision location capability, or use as radar.
- Short duration pulses are able to provide robust performance in dense multi-path environments by exploiting more resolvable paths.

Conveying information with ultra-short duration waveforms, UWB signals have low susceptibility to multipath interference. Multipath interference occurs when a modulated signal arrives at a receiver from different paths. The combining of signals at the receiver can result in the distortion of the received signal. The ultra- short duration of UWB waveforms gives rise to a fine resolution of reflected pulses at the receiver. As a result, UWB transmissions can resolve many paths, and are thus rich in multipath diversity.

The reduced complexity and low cost of UWB systems are due to carrier-free nature of the signal transmission. Specifically, due to its ultra wide bandwidth, the UWB signal may span frequency commonly used as carrier frequency. Hence an additional radio frequency (RF) mixing stage is not required as needed in conventional radio technology. The elimination of up/down-conversion processes and RF components allow the entire UWB transceiver to be integrated with a single CMOS implementation which in turn contributes directly to low cost, small size, and low power.

3.1.2 Applications:

UWB technology can enable a wide variety of applications in wireless communications, networking, radar imaging, and localization systems. For wireless communications, the use of UWB technology under the FCC guidelines [18] offers significant potential for the deployment of two basic communications systems:

- **High data rate short range communications** - high data rate wireless personal area networks (PAN).
- **Low data rate and location tracking** - sensor, positioning, and identification networks.

Apart from this, UWB technology has a wide range of high data rate indoor applications.

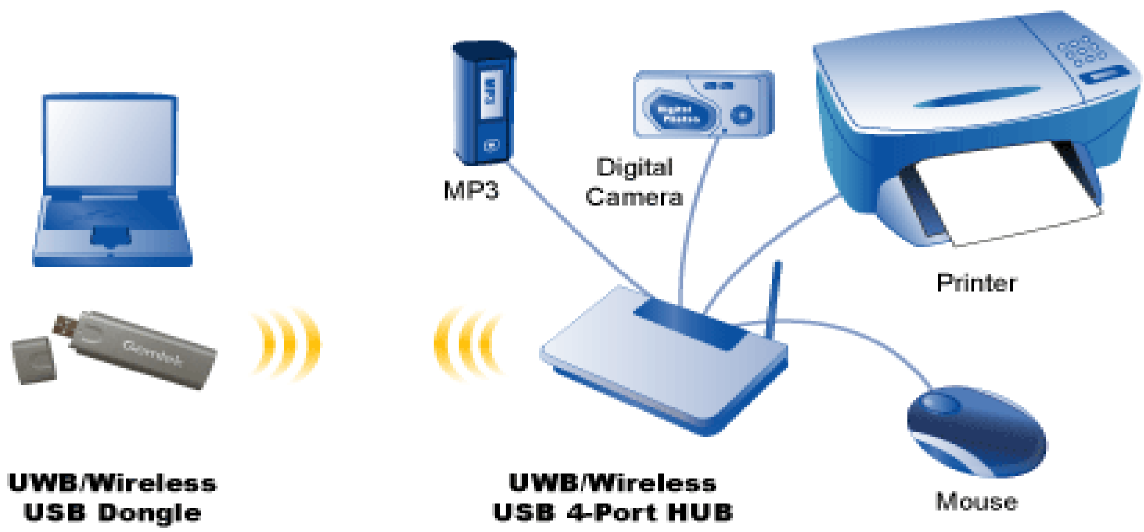


Fig 3.4 UWB indoor applications

High data rate WPANs is defined as networks with medium density of active devices per room (5-10) transmitting at 100 Mbps to 500 Mbps within a distance of 20 m. The ultra-wide bandwidth of UWB enables various WPAN applications such as high-speed wireless universal serial bus (WUSB) connectivity for personal computers (PCs) and PC peripherals, high-quality real-time video and audio transmission, file exchange among storage systems, and cable replacement for home entertainment systems.

Recently, the IEEE 802.15.3 standard task group has established the 802.15.3a study group to define a new physical layer concept for high data rate WPAN applications. The focus of this study group is to standardize UWB wireless radios for indoor WPAN transmissions. The goal of the IEEE 802.15.3a standard is to provide a higher speed physical layer for the existing approved 802.15.3 standard for applications which involve imaging and multimedia. The work of the 802.15.3a study group also includes standardizing the channel model to be used for UWB system evaluation.

Alternatively, UWB can trade- off data rate for increased transmission range. The UWB technology is proved to be beneficial under low rate operation mode and is potentially used in sensor, positioning, and identification networks. A sensor network comprises of a large number of static or dynamic nodes spread over a geographical area to be monitored. Some of the major requirements on the sensor networks are low-cost, low-power and multi-functionality which are well provided by the UWB technology [22]. Moreover, due to the fine time resolution of UWB signal, UWB based sensing has the potential to improve the resolution of conventional proximity and motion sensors. The low rate transmission combined with accurate location tracking capabilities offers an operational mode also known as low data rate and location tracking.

Recently, the IEEE established the 802.15.4 study group to define a new physical layer concept for low data rate applications utilizing UWB technology at the air interface. The study group addresses new applications which require only moderate data throughput, but require long battery life such as low-rate wireless personal area networks, sensors and small networks.

3.1.3 UWB Challenges:

While UWB technology has several attractive properties that make it a promising technology for future short-range wireless communications and many other applications, there are also certain challenges that should be overcome to fulfil these expectations.

The transmitted power level of UWB signals is strictly limited in order for UWB devices to peacefully coexist with other wireless systems. Such strict power limitation poses significant challenges for designing UWB systems. One major challenge is to achieve the desired performance at adequate transmission range using limited transmitted power. Another challenge is to design UWB waveform that efficiently utilizes the bandwidth and power allowed by the FCC spectral mask. Moreover, to ensure that the transmitted power level satisfies the spectral mask, adequate characterization and optimization of transmission techniques (e.g., adaptive power control, duty cycle optimization) may be required.

The ultra-short duration of UWB pulses leads to a large number of resolvable multipath components at the receiver. Particularly, the received UWB signal contains many delayed and scaled replicas of the transmitted pulses. Additionally, each of the resolvable pulses undergoes a different channel fading. These make multipath energy capture a challenging problem in UWB system design. For example, if a RAKE receiver is used to collect the multipath energy, a large number of fingers are needed to achieve desired performance.

Design challenges also exist in the areas of modulation and coding techniques that are suitable for UWB systems. Initially UWB radio was used for military applications where multiuser transmission and achieving high multiuser capacity were not of major concern. However, these issues become prominent in commercial applications such as high-speed wireless home networks. Effective coding and modulation schemes are thus necessary to improve UWB multiuser capacity in addition to system performance.

The impact of narrowband interference on UWB receivers is a major design challenge. Specifically, the UWB frequency band overlaps with that for the IEEE 802.11a wireless local area networks (WLANs). The signals from 802.11a devices represent in-band interference for the UWB receiver front-end.

Other design challenges include scalable system architectures and spectrum flexibility. UWB potential applications include both high rate applications (e.g. images and video), and lower rate applications (e.g. computer peripheral support). Thus it is necessary that the UWB transceiver can support a wide range of data rates. Furthermore, the unlicensed nature of the UWB spectrum makes it essential for UWB devices to coexist with other devices that share the same spectrum. However, it is challenging to design UWB systems with spectrum flexibility that allow UWB devices to coexist effectively with other wireless technologies and to meet potentially different regulatory requirements in different regions of the world.

3.2 Multiple antenna Techniques:

Traditionally, wireless communications were used for voice and small data transfers while most of the high-rate data transfer products used wired communications. However in the recent years wireless multimedia applications, such as cell phones having an integrated camera, emailing capability and GPS have been increased. As a result there are more requirements for wireless high speed data transfers which traditional antennas are not capable of delivering because of multipath and co-channel interference [23].

In addition to the needs of high speed data transfers, there is also an issue of quality control, which includes low error rate and high capacity. In order to maintain certain Quality of Service (QoS), multipath fading effect has to be dealt with. As the transmitted signal is reflected on to various objects on its way to the receiver, the signal is faded and distorted. This phenomenon is called multipath fading. Co-channel interference refers to the interference caused by different signals using the same frequency.

Hence multiple antennas are to reduce the error rate as well as to improve the quality and capacity of a wireless transmission. This is done by directing the radiation only to the intended direction and adjusting the radiation according to the traffic condition and signal environment. All multiple antennas are equipped with several antennas either in the transmitter or the receiver or both of them. A sophisticated signal processor and coding technology are the key factors in multiple antennas. Multiple antenna techniques can be broken down into three categories namely, Spatial Diversity (SD), Spatial Multiplexing (SM) and Adaptive Antenna System (AAS).

3.2.1 Spatial Diversity:

Spatial diversity is a part of antenna diversity techniques in which multiple antennas are used to improve the quality and reliability of a wireless link. Usually in densely populated areas, there is no clear Line of Sight (LoS) between the transmitter and the receiver. As a result, multipath fading effect occurs on the transmission path. In spatial diversity several receive and transmit antennas are placed at a distance from one another. Thus if one antenna experiences a fade, another one will have an LoS or a clear signal. Figure 3.5 shows the basic principle of Spatial Diversity.

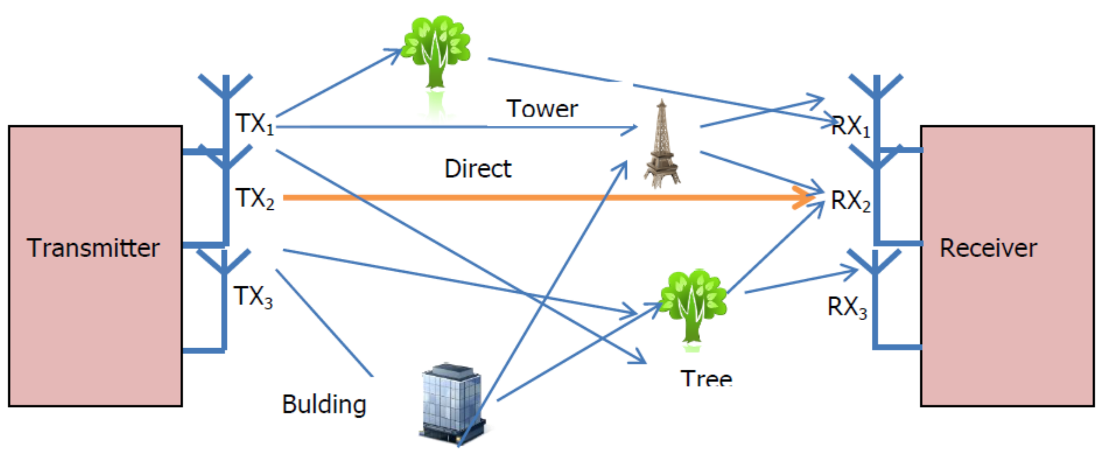


Fig. 3.5 Spatial Diversity

In figure 3.5 several antennas are placed at a distance from one another. There are various obstacles on the signal's path. However, it can be noticed in the figure that from transmitter TX_1 there is a clear LoS to receiver RX_2. Despite the multipath fading effect having occurred in other receivers, the receiver can get a fairly good signal.

In the case of base stations in a macro cellular environment, with large cells with high antennas, a distance up to 10 wavelengths is needed to ensure a low mutual fading correlation. However, in case of hand held devices, because of lack of space, half of wavelength is enough for the expected result. The reason behind this space is usually in the macro/cell scenario, the fading of which is caused by multipath correlations that have occurred in the near zone of the terminal. Therefore, from the terminal side, different paths arrive in a much wider angle, thus requiring smaller distances, whereas from the transmitter side, the path angle is relatively low. That is why a larger distance is required.

3.2.2 Spatial Multiplexing:

Multiple antenna systems can establish parallel data streams through different antennas. This is to be done in order to increase the data transfer rate. This process is called spatial multiplexing [23].

The bit stream which is to be transmitted is divided or demultiplexed into several data segments. These segments are then transmitted through different antennas simultaneously. Since several antennas are in use, bit rate increases rapidly without the requirement of extra bandwidth or extra transmission power. The signal captured by the receiving antenna is a combination of all individual segments. All of them are separated at the receiver using an interference cancellation algorithm. A well-known multiplexing scheme known as BLAST was developed by Bell Labs.

3.2.3 Adaptive Antenna System:

In adaptive antenna systems, multiple antennas are used both in the transmitting and receiving side of a communication link to optimize the transmission over the channel. An AAS system will focus its transmit energy towards a receiver and it will focus its energy towards the transmitter while receiving. The technique used in the AAS is known as beam forming. Figure 3.6 shows the basic principle of AAS.

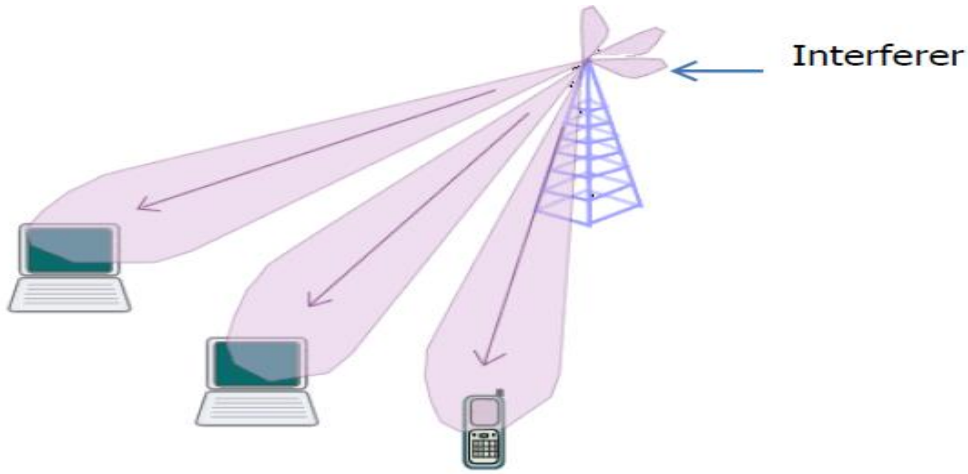


Fig. 3.6 Adaptive Antenna System.

The beam forming enables directional signal transmission or reception without manually steering the antennas. In this beam forming technique, several transmitters are set apart from one another. They all transmit the same signal with different phase differences and delay. As a result, the interference that occurred in all the transmitters can be used to steer a signal to a particular direction. In adaptive antenna systems, signals can be focused simultaneously on many remote devices. The shape of these beams can be controlled in such a way that the strength of signal between the transmitter and receiver is always maximum.

The adaptive antenna system can increase the link quality by combining the effects of multipath propagation as well as by exploiting different data streams from different antennas. The following are the key benefits of AAS [23]:

- **Increased coverage**: The adaptive antenna can increase the coverage of a wireless transmission by increasing the gain. Typically, the adaptive antenna gain depends on the number of array elements. For example, a six element array antenna can provide a gain of six.
- **Increased capacity**: One of the main advantages of AAS is its increased capacity. Usually, signals can be interfered by other users in highly populated areas. Therefore, the Signal to Noise Ratio (SNR) will be normally higher than the Signal to Interference Ratio (SIR). Experiments have shown that the adaptive antenna system can increase SIR up to 10dB, thereby increasing the overall capacity.

- **Cost reduction:** As AAS concentrates on individual users, lower power consumption and lower amplifier cost are easily achievable.
- **Improved link quality and reliability**: As signals are sent individually to the remote devices, diversity gain is obtained in the receiver by receiving individual parts of the same signal. Diversity gain is the gain in the receiver and it is caused by using two or more antennas. The strength of one of the signals can be maximum and thus the link quality is maximized.
- **Increased Spectral efficiency:** Spectral efficiency is the process of using the available spectrum or bandwidth in such a way that the data transmission rate is maximum with fewest transmission errors. Spectral efficiency plays a vital role in cost assumption for the operator. It also gives a hint about the required number of base stations, the total required amount of spectrum, the required number of sites and the overall consumer affordability.
- **Security:** It is very difficult to tap an AAS system, as the intruder must stand in the direction of the signal flow.
- **Location based services:** Since the location of the user is always known to the transmitter, various location based services can be implemented in the adaptive antenna system.

However, there are some disadvantages of the adaptive antenna system, such as complex transceiver mechanism, need of resource management and physical size of the antennas.

3.3 MIMO:

MULTIPLE-INPUT-MULTIPLE-OUTPUT (MIMO) technology has attracted attention in modern wireless communication systems. A significant increase in channel capacity is achieved without the need of additional bandwidth or transmit power by deploying multiple antennas for transmission to achieve an array gain and diversity gain, thereby improving the spectral efficiency and reliability. MIMO antenna systems require high decoupling between antenna ports and a compact size for application in portable devices.

Fig 3.7 MIMO system

Multiple-Input Multiple-Output (MIMO) uses multiple antennas on both the transmitter and receiver. They have dual capability of combining the SIMO and MISO technologies. They can also increase capacity by using Spatial Multiplexing (SM). The MIMO method has some clear advantages over Single-input Single-output (SISO) methods. The fading is greatly eliminated by spatial diversity, low power is required compared to other techniques in MIMO.

3.3.1 Basic Building Block of MIMO:

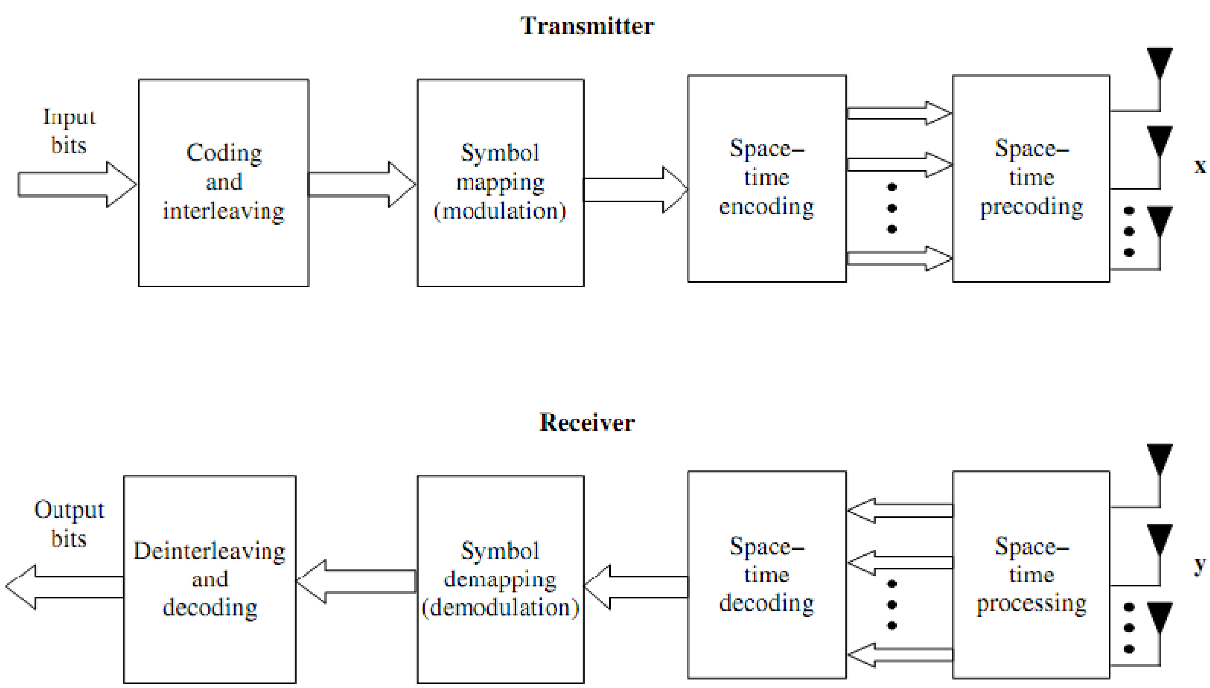


Fig. 3.8 Building Blocks of a MIMO system.

The basic building blocks of a MIMO system are shown in the figure. In this figure, x and y represent the transmitted and received signal vectors respectively. At first, the information to be transmitted is encoded and interleaved. The symbol mapper maps the encoded information to data symbols. These data symbols are then fed into a space-time encoder which creates some spatial data streams. The data streams are then transmitted by different antennas. The transmitted signals are propagated through channels and are received by receiving arrays. The receiver then collects all the data from the antennas and reverses the operation to decode the data using a space-time processor, space time decoder, symbol de-mapper and at last the decoder.

3.3.2 MIMO Channel Model:

The MIMO channel communication takes advantage of multipath propagation. The MIMO channel can be described by the following matrix:

$$y = Hx + n$$

Where y is the received signal vector, x is the transmitted signal vector, H and n are the channel matrices.

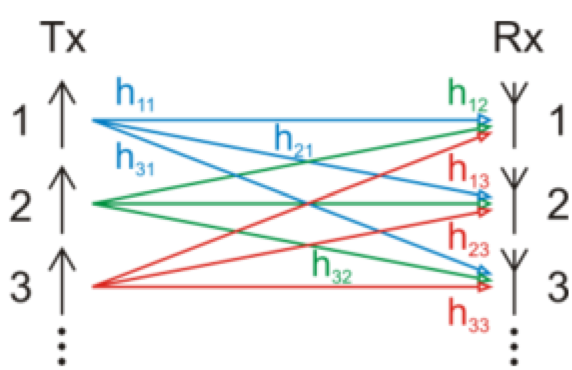


Fig. 3.9 MIMO Channel Model.

In order to understand MIMO better, it is necessary to look into its channel model as shown in Figure. For a system with M_T transmitters and M_R receivers, the MIMO channel at a given time may be represented by $M_R \times M_T$ matrix as demonstrated below,

$$H = \begin{bmatrix} H_{1,1} & H_{1,2} & \cdots & H_{1,M_T} \\ H_{2,1} & H_{2,2} & \cdots & H_{2,M_T} \\ \vdots & \vdots & \ddots & \vdots \\ H_{M_R,1} & H_{M_R,2} & \cdots & H_{M_R,M_T} \end{bmatrix},$$

Where $H_{m,n}$ is the channel gain between the *m*-th receive and *n*-th transmit antenna. The *n*-th column of H is called as the spatial signature of the *n*-th transmit antenna. The geometry of M_T differentiates the signals launched from the transmitter.

3.3.3 MIMO Channel Capacity:

The theoretical capacity of the MIMO channel is expressed by the following formula:

$$C = E_H\left[log_2 det\left(I_{Mr} + \frac{\rho}{M_t} HQH^H\right)\right] \quad (3\text{-}3)$$

Where $Q = E\left[xx^H\right]$ is the input covariance matrix and ρ (SNR) = $\frac{E_S}{N_0}$

E_S - Total transmit power;

N_0 – Noise power in each antenna.

In equation (3-3), the capacity depends on the antenna numbers, input covariance matrix and the channel statistics. The matrix Q is diagonal and all the elements are real numbers.

There are two cases for this matrix. When the transmitter is an uninformed transmitter, i.e. when it does not have proper knowledge of the channel matrix, then the matrix will be same as the identity matrix, $Q = I_{Mt}$. In other words, the total transmitted power will be divided across all the antennas by the transmitter.

In the case of an informed transmitter, i.e. when the transmitter has knowledge of the channel matrix, the capacity will be optimized by using the so-called waterfilling principle. Here, various levels of transmit power will be distributed among various transmitting antennas depending on their channel strength. The better the channel is, the more power it gets and vice versa.

3.3.4 Forms of MIMO:

The Multiple Input multiple Output (MIMO) method can be divided into various forms depending on uses [24]. MIMO is basically the combination of all the multiple antenna techniques such as SISO, SIMO and MISO. It can use the beam forming or the spatial Multiplexing methods. MIMO can be categorized into two types, multi-antenna types and multi-user types. Multi-antenna types are listed below:

- SISO (Single-input Single-output) - is a conventional radio system where neither the transmitter nor receiver have multiple antenna.
- SIMO (Single-input Multiple-output) - is a special case when the transmitter has a single antenna.
- MISO (Multiple-input Single-output) - is a special case when the receiver has a single antenna.

Applications:

- Spatial multiplexing techniques make the receivers very complex, and therefore they are typically combined with Orthogonal Frequency Division Multiple Access (OFDMA) modulation, where the problems created by a multi-path channel are handled efficiently. The IEEE 802.16e standard incorporates MIMO-OFDMA.

- MIMO is also planned to be used in Mobile radio telephone standards such as recent 3GPP and 3GPP2.

- MIMO technology can be used in non-wireless communications systems
    - home networking standard ITU-T G.9963, which defines a powerline communications system uses MIMO techniques to transmit multiple signals over multiple AC wires (phase, neutral and ground).

Limitations:

The physical antenna spacing is selected to be large; multiple wavelengths at the base station. The antenna separation at the receiver is heavily space constrained in hand sets, though advanced antenna design and algorithm techniques are under discussion.

3.4 Ultra-wideband MIMO Antennas:

Recently, there is a demand to increase the data rate of existing wireless communication systems. The application of diversity techniques, most commonly assuming two antennas in a mobile terminal, can enhance the data rate and reliability without sacrificing additional spectrum or transmitted power in rich scattering environments. MIMO UWB systems can further increase the channel capacity as compared to conventional MIMO systems for narrowband applications. To combat the multipath fading problem in an indoor UWB wireless communication system, an UWB diversity antenna system is a promising candidate. However, for a MIMO antenna to be implemented in a multifunctional portable device, the following challenges are to be considered during the design of these antennas.

3.4.1 Design Challenges in UWB MIMO antenna systems:

- **Isolation**: Mutual coupling between antennas is a major concern while designing MIMO systems. Mutual coupling not only affects the antenna efficiency but also influences the correlation. Isolation better than -16 dB is required throughout the operating region of the antenna system.

- **<u>Bandwidth:</u>** Return loss (S_{11} in dB) should be less than -10 dB from 3.1 to 10.6 GHz so that the impedance bandwidth covers the entire UWB. Simultaneous enhancement of isolation and impedance bandwidth in a single antenna structure is one of the toughest challenges that exist in the design of a UWB MIMO antenna system.

- **<u>Size:</u>** Recently, MIMO has been adapted to mobile phones, which use various communication technologies such as WCDMA, WiMAX, WLAN, and UWB in order to realize high speed data transmission. Obviously, such an application requires a compact wide-band MIMO antenna because of the limited space available in wireless devices.

Hence a compact UWB MIMO antenna system with low mutual coupling among the antennas is desired for UWB applications.

3.4.2 Isolation and Bandwidth Enhancement:

Various methods and isolation structures can be introduced for simultaneous enhancement of bandwidth and isolation in a UWB MIMO antenna system.

Mutual coupling can be reduced by introducing reflectors in the ground plane. Stubs are introduced in some designs to reduce mutual coupling. To increase impedance bandwidth, slots can be introduced in the patch. Several studies have been carried out on various MIMO antenna systems with two and four radiating elements and various methods have been proposed to improve isolation between the antenna elements. Various structures like mushroom–shaped EBG structures have been proposed to reduce mutual coupling by suppressing the ground current flowing between the radiating elements. Low mutual coupling can also be achieved through neutralization techniques and decoupling networks. Recently, Defected Ground Structures (DGS) are introduced to improve antenna performance characteristics like size reduction, gain and bandwidth enhancement, and they are also used in reduction of mutual coupling between antenna elements.

3.4.3 Literature Review:

Many studies have been made to reduce the size of the antennas and for increasing the isolation and impedance bandwidths for MIMO/diversity UWB antenna systems.

In [25], a UWB diversity monopole antenna has been designed, and a T-shaped reflector has been introduced between the two radiators to reduce the mutual coupling. The operating range of the antenna is from 2.3–7.7 GHz. Another diversity UWB antenna has been proposed in [26], and the impedance bandwidth is from 3.1 to 5.8 GHz. The isolation can be increased through a slot etched on a T-shaped reflector. In [10], a diversity antenna for PDA application has been proposed, and it covers the band of 2.27–10.2 GHz. Three stubs have been introduced to reduce the mutual coupling. However, the size of the antennas in [25]–[26] are still relatively large. Recently, an UWB diversity antenna with a small size has been proposed in [9]. The antenna has a size of 37 × 45 mm, and good isolation has been achieved. However, the operating frequency of the antenna in [9] is from 3.1 to 5 GHz (lower UWB) and cannot cover the entire band of 3.1–10.6 GHz. Low mutual coupling is also difficult to achieve in the whole UWB with the decoupling structure in [9].

In [27]–[29], slot technique was introduced to achieve low mutual coupling. The slot technique can be explained as a slow wave structure, which decreases the wavelength of the signal and thus increase the separation between antenna elements [27]. Besides, a protruding T-shaped stub in the ground plane was used to improve the mutual coupling between antenna elements [30], [31]. Similarly, a T-shaped and dual-inverted-L-shaped ground branch was added to obtain low mutual coupling [32]–[34]. Then, in [35], the ground branch technique was analyzed, and by adding a suitable ground branch, a dual-element Inverted-F antenna with low mutual coupling was designed. The study demonstrated that the technique creates an additional coupling path to cancel out the original coupling. In addition, neutralization technique was proposed, in which a neutralization line was added between the feeding strips or the shorting strips of the PIFAs [36]–[38]. Similar to the neutralizing principle, lumped circuits or neutralization lines were applied between planar monopoles [39], [40]. Considering all these studies, most of them have a common idea of adopting some structure to create reverse coupling to reduce mutual coupling.

In general, two, four or more than four elements are used in the existing MIMO antennas. However, when the number of elements increase, mutual coupling and complexity increases. Hence, for an efficient design and analysis, two-element MIMO antennas are considered in this work, which will be presented in the following chapters.

Chapter 4

A Compact two element UWB MIMO Antenna

In this chapter, design and analysis of a two- element MIMO antenna system is presented. The proposed MIMO antenna system has a compact size of 35 mm × 40 mm and has an operating band from 4.4 to 10.7 GHz, covering almost the entire UWB. A fork-shaped structure is extended from the ground plane to enhance the isolation to < -20 dB in most of the UWB band.

4.1 Antenna Design:

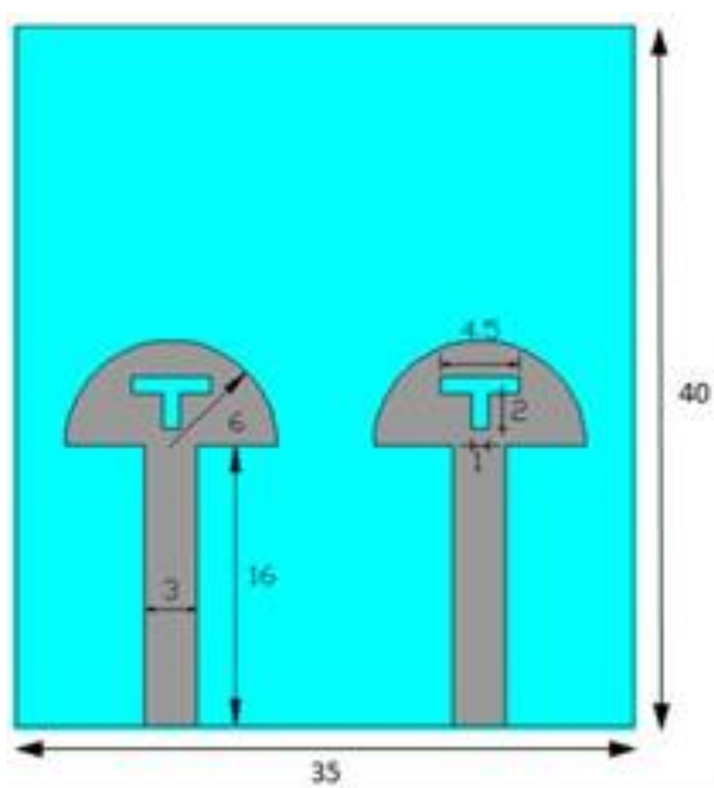


Fig.4.1. Geometry of the proposed antenna system. (a) Front view

The geometry of the proposed UWB MIMO antenna system is shown in Fig.4.1. The antenna system consists of two radiating elements of similar geometry printed on a common FR4 substrate of thickness 1.6 mm and a compact size of 35 mm × 40 mm. The relative permittivity of the substrate is 4.4. A semicircular disc monopole is chosen as the radiating element and each of the radiators is fed separately by a 50Ω microstrip line. Circular and semicircular monopole antennas have more impedance bandwidth than the rectangular, triangular, square and hexagonal monopole antennas. Semicircular geometry of the radiator provides more isolation between the radiating elements than most other existing geometries. The two radiators are placed in such a way that distance between them is more than half of the wavelength of the lowest frequency in order to achieve the isolation between the radiating elements. The gap between the radiating element and the ground plane affects the impedance bandwidth and hence the distance is optimized at 1 mm. A central T-shaped slot of 1 mm width is introduced on each of the radiators to enhance the impedance bandwidth. A fork-shaped structure along with a single branch arising from the center of the ground plane improves the wideband isolation between the radiating elements.

4.2 Proposed Isolation Mechanism:

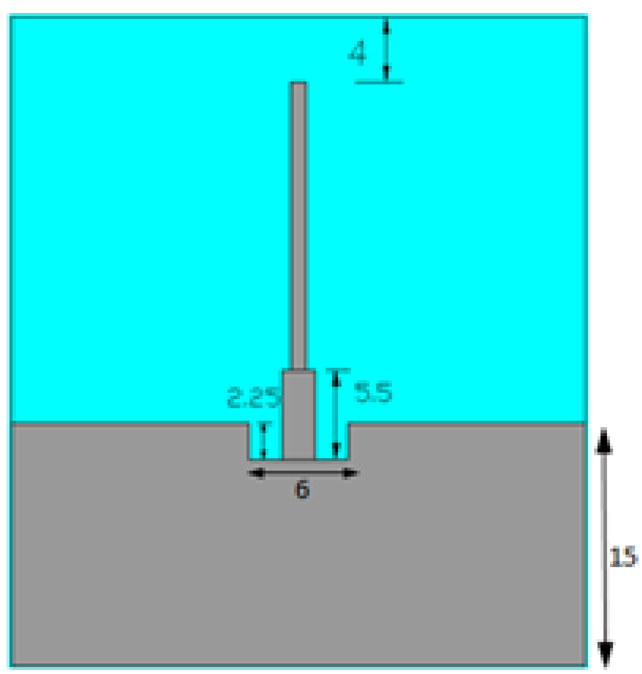


Fig.4.2. Geometry of the proposed antenna system. Rear view (1)

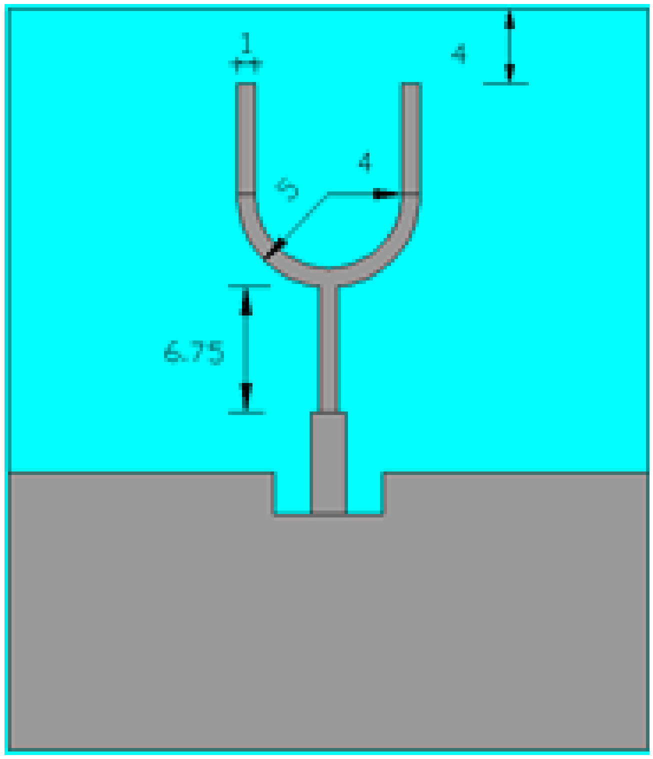


Fig.4.3. Geometry of the proposed antenna system. Rear view (2)

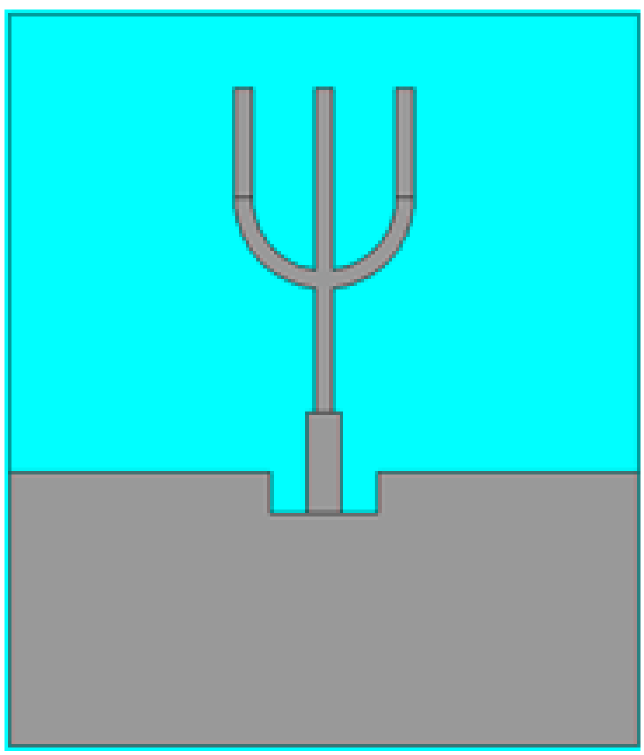


Fig.4.4 Geometry of the proposed antenna system. Rear view (3)

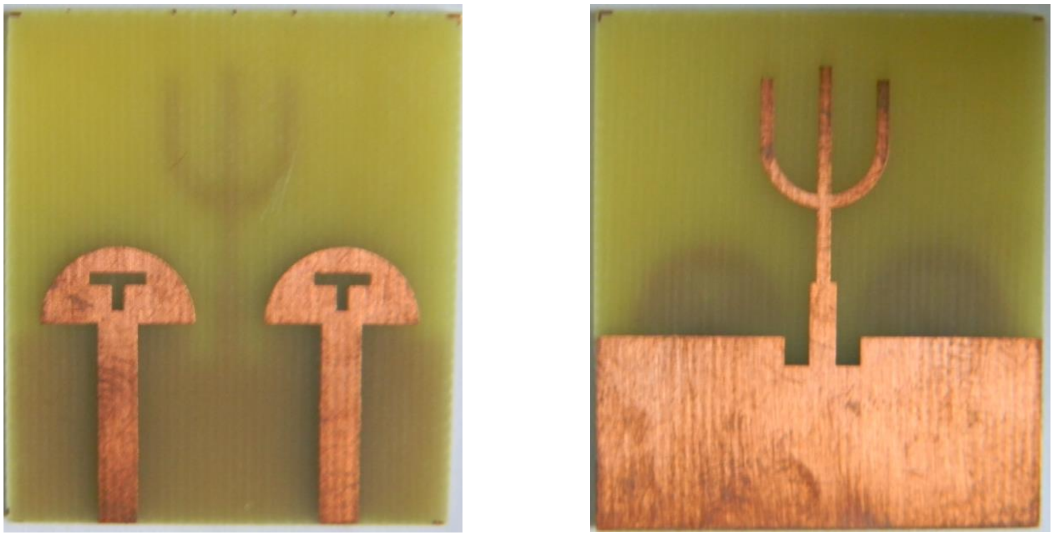


Fig.4.5 Prototype of the proposed MIMO antenna system

Reflecting structures are introduced in the ground plane to reduce mutual coupling between the antennas. A single branch of length 16.75 mm extends from the center of a notched block in the ground plane [Fig.4.2], which acts as a reflector, thereby providing isolation between the antennas. Then a fork-shaped structure is introduced instead of the center branch [Fig.4.3]. When one of the ports feeding the radiators is excited, the designed structures extending from the ground plane obstruct the surface current flowing to the other radiator through the ground plane, thereby weakening the coupling between the radiators. Finally, the fork-shaped structure is introduced along with the center branch [Fig.4.4]. The resulting isolation structure has a center reflector and two branches, introduced due to the fork-shaped structure. More resonances will be introduced when the number of branches or structures increase, and hence isolation is enhanced throughout the UWB.

4.3 Simulation Results & Antenna Performance Characteristics:

The proposed antenna with the various ground plane structures is simulated using the commercial software CST MICROWAVE STUDIO. The simulated results of S-parameters and radiation pattern are obtained in the frequency range of 3-11 GHz and analyzed for isolation and bandwidth performance characteristics.

4.3.1 Bandwidth Characteristics:

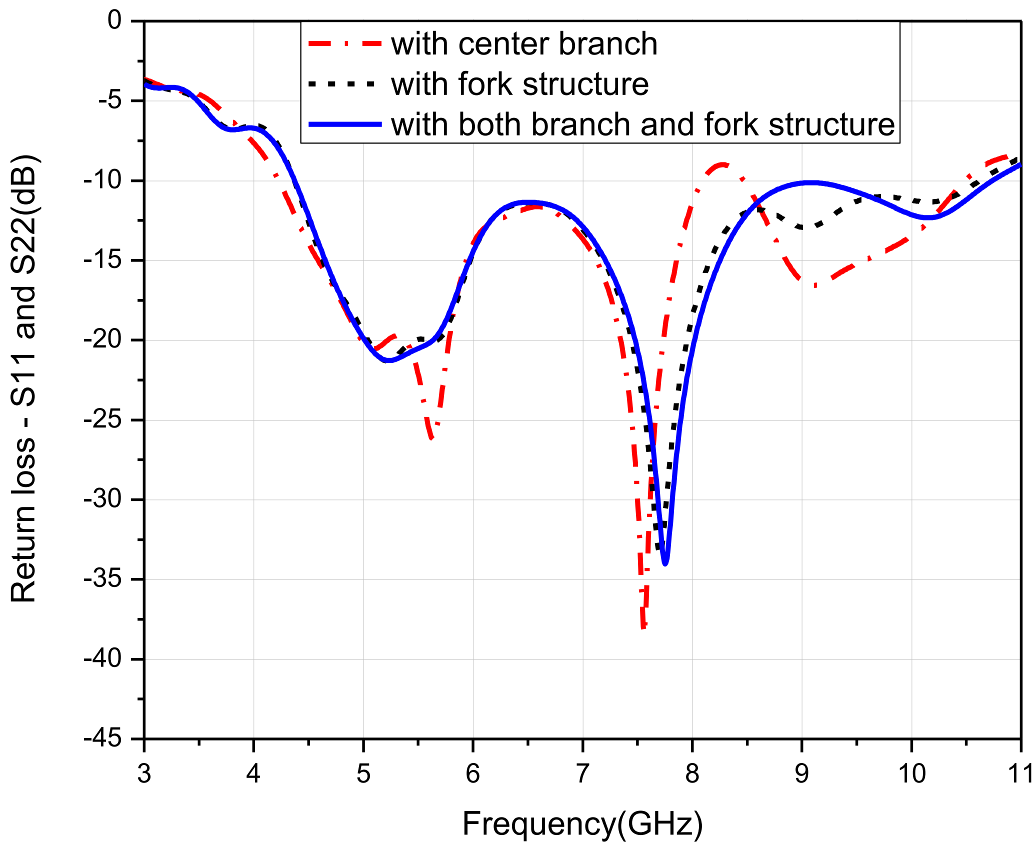


Fig.4.6. Simulated S_{11} and S_{22} of the proposed antenna system

Simulated results of S_{11} and S_{22} of the MIMO antenna system with and without the fork-shaped structure are shown in Fig.4.6. Both S_{11} and S_{22} are found to be same due to symmetry of the antennas. According to the simulated results, S_{11} (Return loss) is found to be less than -10 dB from 4.4-10.7 GHz after the addition of the fork-shaped structure. Hence the bandwidth is increased to cover almost the entire UWB by introducing the fork-shaped structure.

4.3.2 Isolation Characteristics:

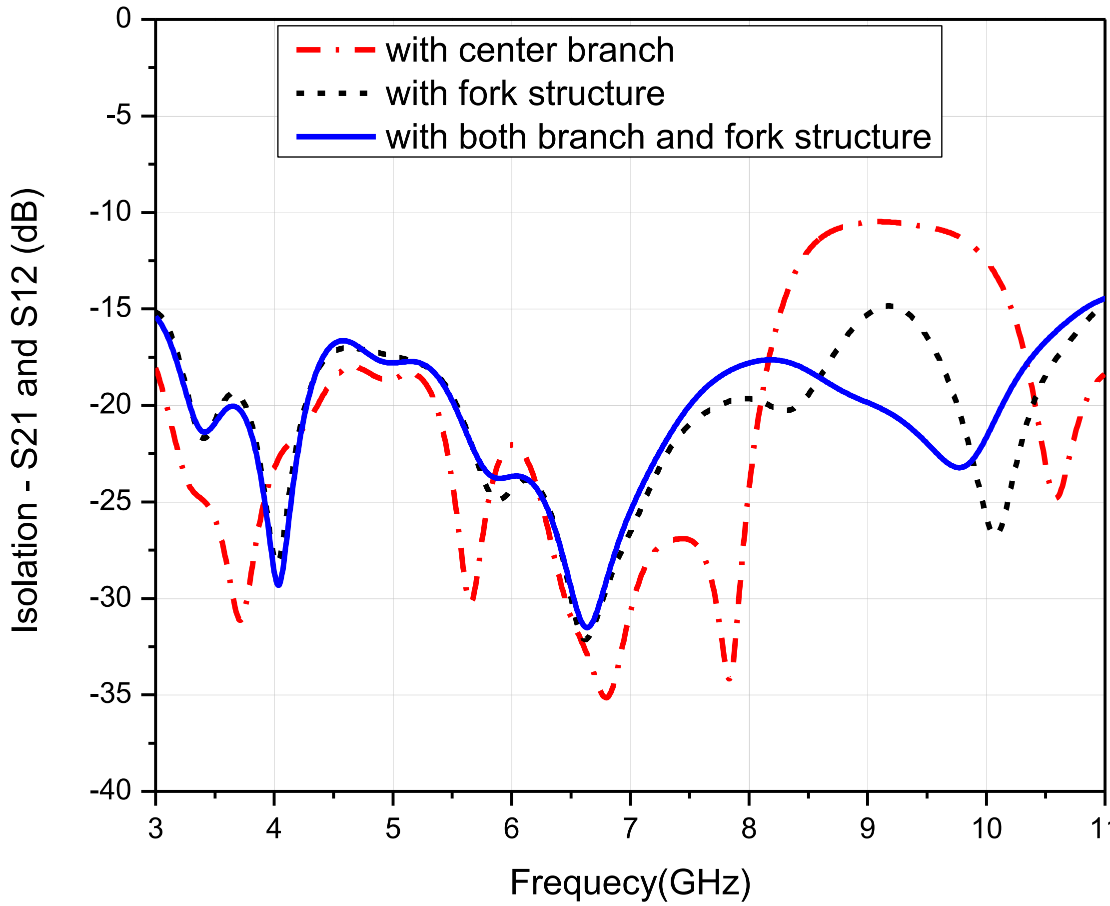
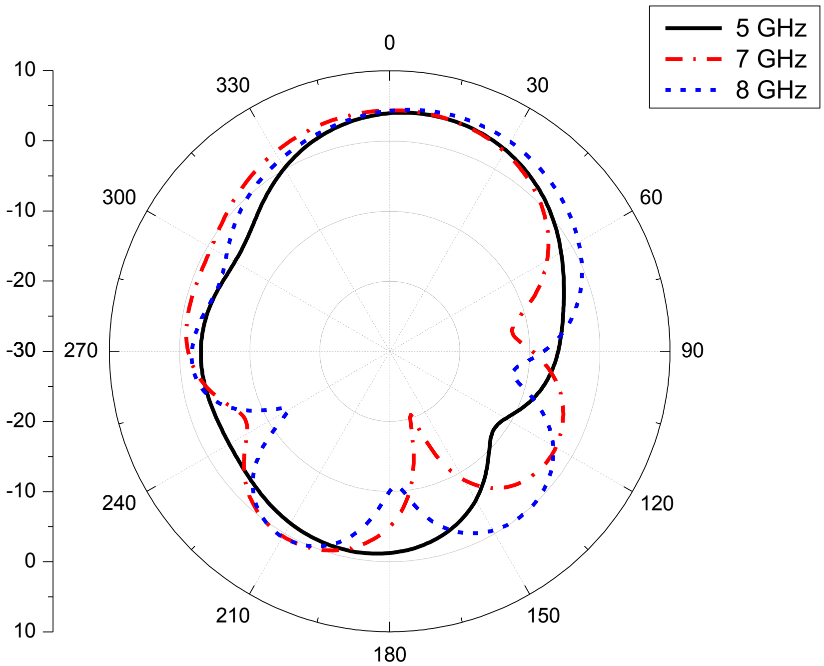


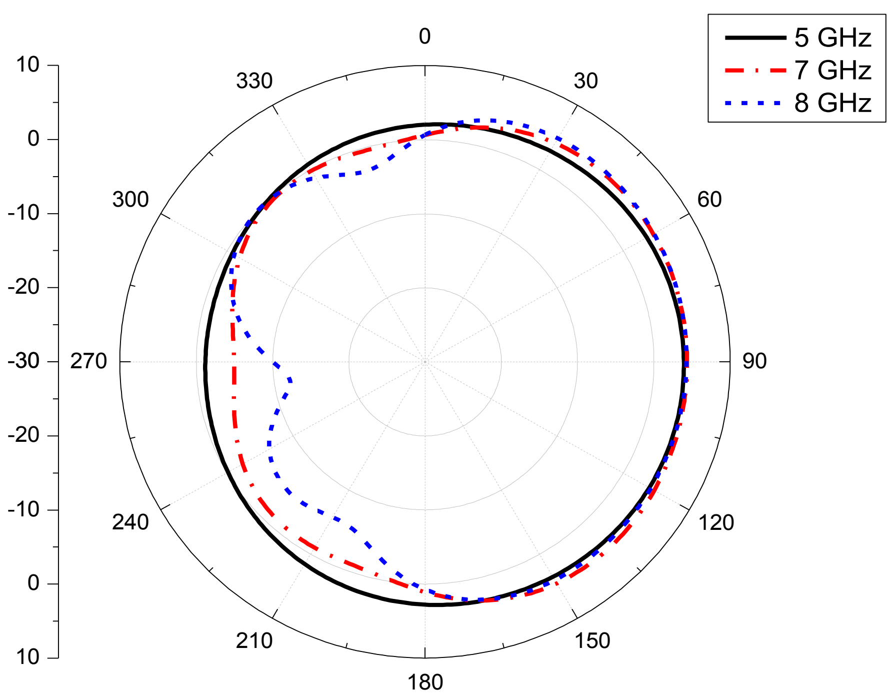
Fig.4.7. Simulated S_{21} and S_{12} of the proposed antenna system.

Simulated results of S_{21} and S_{12} are shown in Fig.4.7. S_{21} is found to be less than -15 dB throughout the band after introducing the fork-shaped structure. With the center branch and the fork structure together, better isolation of more than -17 dB is achieved throughout the UWB and more than -20 dB in most of the band. This result satisfies the required condition that the mutual coupling between the antennas is to be lower than -15 dB for proper operation of the MIMO system in the UWB range.

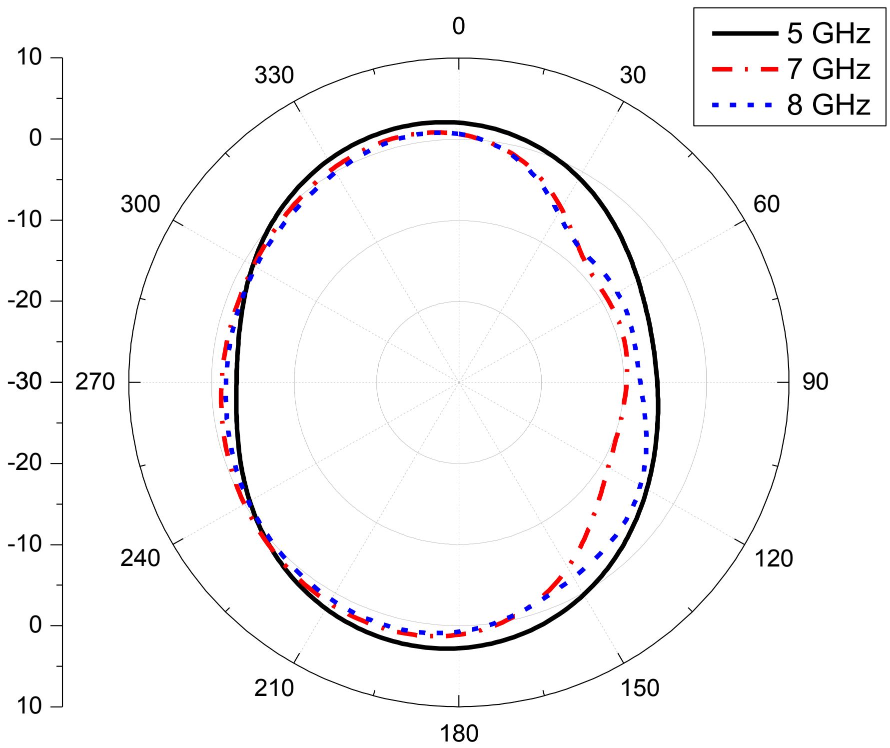
4.3.3 Radiation Performance:



(a).



(b)



(c)

Fig.4.8. Simulated radiation patterns of the proposed antenna system: (a) x-y plane, (b) x-z plane, (c) y-z plane

The radiation characteristics of the proposed antenna system are investigated in the operating frequency range of 4.4-10.7 GHz. Simulated radiation patterns for one port are shown in Fig.4.8 at frequencies of 5,7 and 8 GHz, in the three principal planes at $\theta = 90^0$,$\phi = 0^0$ and $\phi = 90^0$, corresponding to the x-y, x-z and y-z planes respectively. The radiation pattern is found to be nearly omni-directional at 5 GHz and more directional at 7 GHz. The radiation patterns are stable across the UWB. The radiation patterns are obtained at one port, while terminating the other port at 50 Ω load.

4.3.4 Antenna Gain

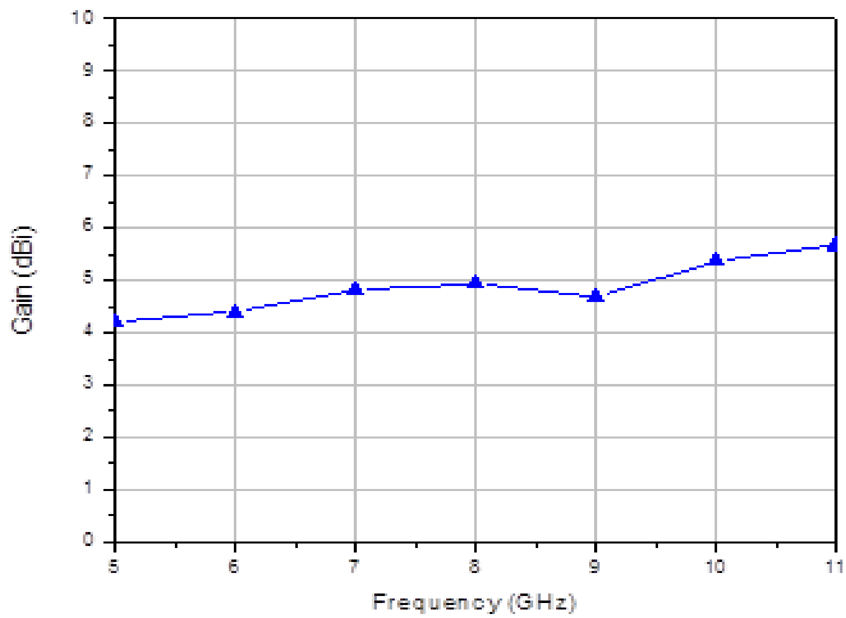


Fig. 4.9 Simulated Antenna Gain.

The antenna gain has been simulated and plotted in Figure 4.9 in the UWB from 5 to 11 GHz. Due to symmetry of structure, the gains of two radiators are same. Hence the gain for one port is presented. The variation of antenna gain across the UWB is within 2 dBi.

Chapter 5

A Hexagonal MIMO Antenna System with DGS

In this chapter, a compact planar MIMO antenna system of size 36 mm × 40 mm with two hexagonal monopole elements is presented. The impedance bandwidth and isolation are enhanced by a hexagonal shaped Defected Ground Structure (DGS).

5.1 Introduction to DGS:

Defected Ground Structure or DGS is one of the new concepts applied to distributed microwave circuits, where the ground plane of a microstrip circuit or antenna is modified in order to enhance the performance of the antenna. The basic element of a DGS is a resonant slot or gap in the ground plane aligned with the transmission line in order to provide efficient coupling to the line.

Recently, Defected Ground Structures (DGS) are introduced to improve antenna performance characteristics like size reduction, gain and bandwidth enhancement, and it is also used in reduction of mutual coupling between antenna elements. The cross- polarized radiation of a microstrip antenna was reduced by 8 dB by introducing a circular DGS [41]. In [42], a double U- shaped DGS was proposed to broaden impedance bandwidth of a monopole antenna by 112%. Enhanced isolation of more than 40 dB is achieved by a dumbbell like DGS [7], but with very low impedance bandwidth. However, to the best of our knowledge, simultaneous enhancement of isolation and impedance bandwidth using a single DGS has yet not been proposed in existing studies.

In the proposed antenna design presented in this chapter, a single hexagonal- shaped DGS is introduced in the ground plane of a two- element compact MIMO antenna system. Different from the traditional DGS, the hexagonal shaped DGS enhances isolation and at the same time broadens the impedance bandwidth of the proposed antenna system.

5.2 Antenna Design:

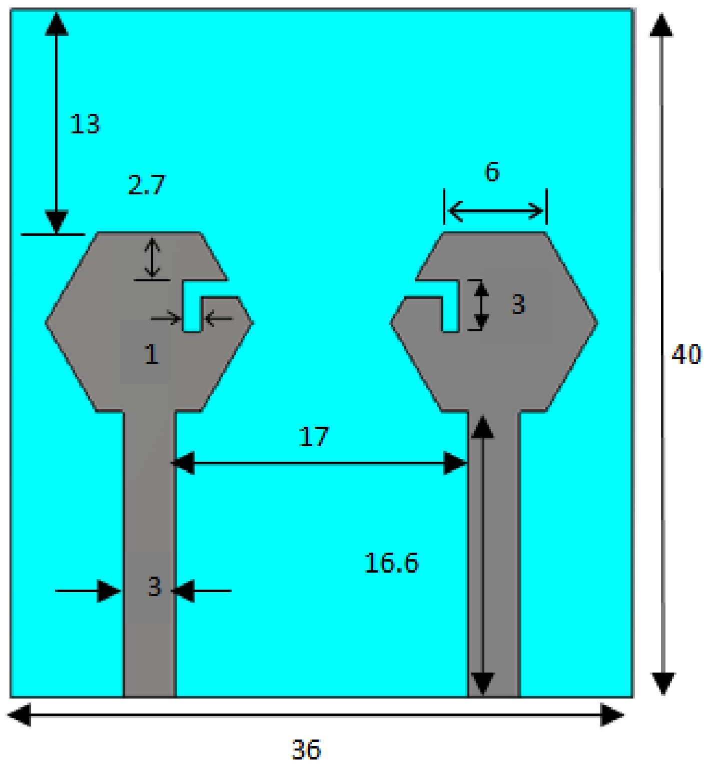


Fig. 5.1 Geometry of the proposed MIMO antenna system- Front view

The two- element MIMO antenna system of a compact size of 36 mm × 40 mm with the proposed DGS is shown in Fig.5.1. The antenna system is printed on a FR4 substrate with a dielectric constant of 4.4 and thickness of 1.6 mm. Each radiator is fed through a 50-Ω microstrip line. The length and width of the microstrip line is 16.6 mm and 3 mm respectively. The distance between the two feedlines is optimized at 17 mm so as to minimize the surface current flowing to the other port, thereby reducing the coupling between the elements. The radiators have a similar, regular hexagonal geometry of side 6 mm, offering more impedance bandwidth than the antennas with rectangular, square or triangular geometries. A slot of 1 mm width is etched on each of the hexagonal antenna elements to adjust the bandwidth, which is determined by the length of the slot.

5.3 Proposed DGS:

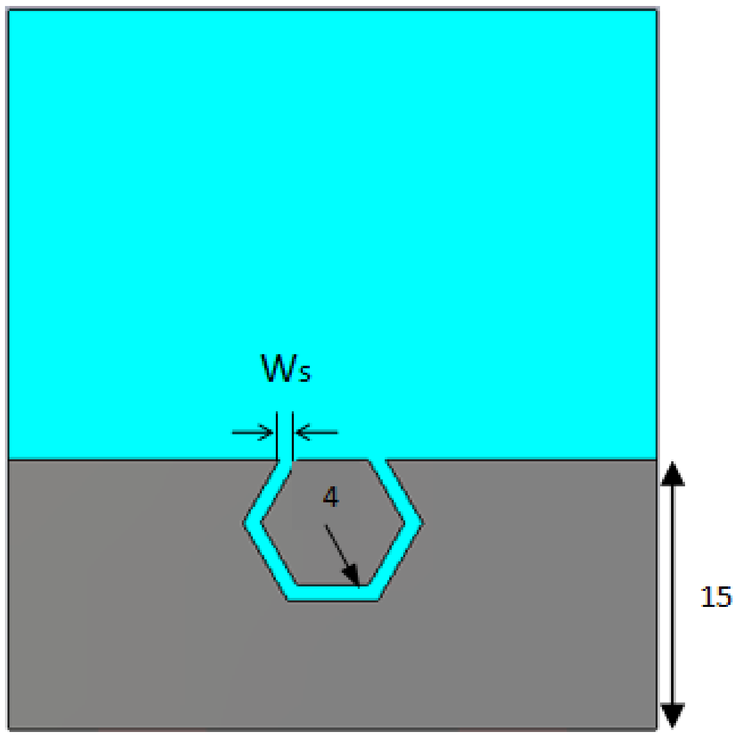


Fig. 5.2 Geometry of the proposed DGS

A defected ground structure (DGS) is introduced as shown in Fig. 5.2, to enhance the bandwidth and to reduce the coupling between the antennas. A hexagonal slot of uniform width W_s = 1 mm is etched on the ground plane. The distance between hexagonal radiator and the hexagonal DGS is optimized at 1.6 mm. Varying this gap, adjusts the impedance bandwidth of the antenna system. The proposed hexagonal – shaped DGS offers a high order matching network for enhancing the bandwidth and at the same time acts as an isolation structure by suppressing the ground current flowing between the two ports, thereby enhancing isolation between the antenna elements.

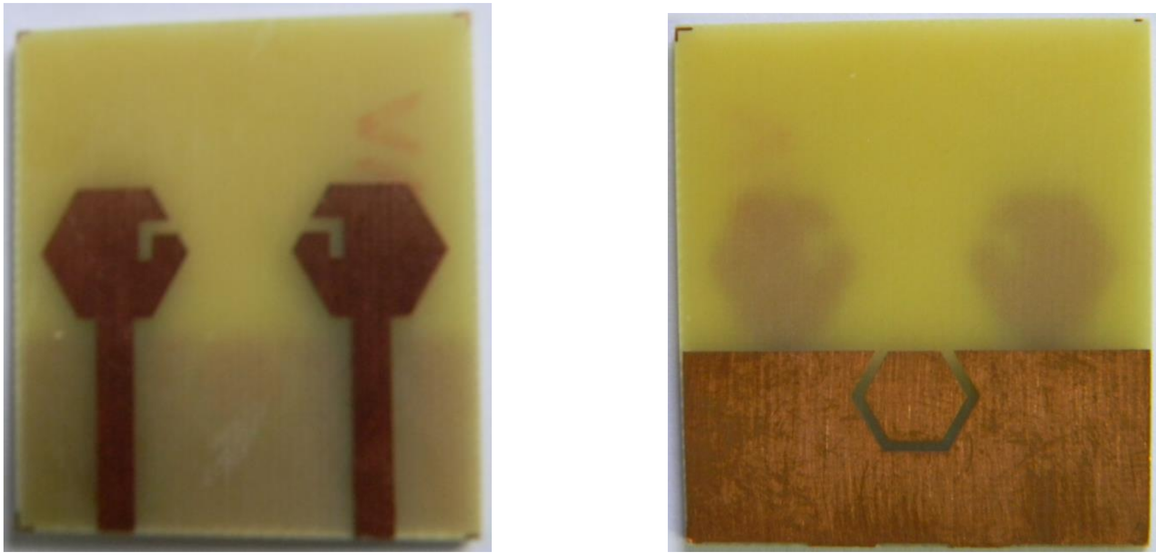
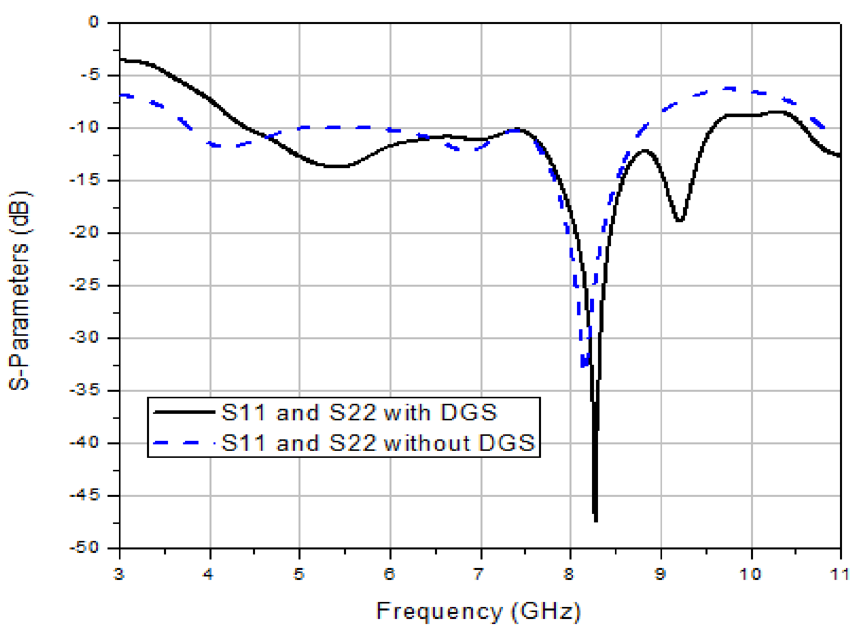


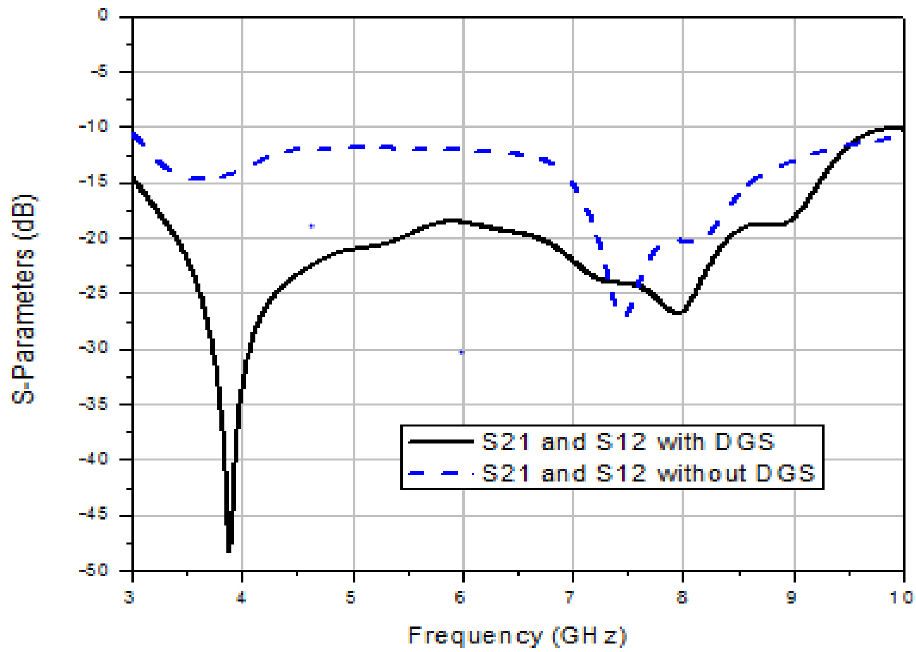
Fig.5.3 Prototype of the MIMO antenna system with DGS

5.4 Simulation Results and Discussions:

Isolation and return loss characteristics of the MIMO antenna system with and without DGS are analyzed to find out the effectiveness of the proposed DGS.



(a)



(b)

Fig.5.4 Simulated S-parameters with and without DGS: (a) S_{11} and S_{22}, (b) S_{21} and S_{12}.

Simulated results of S- parameters with and without DGS are shown in Fig. 5.4. S_{11} is less than -10 dB from 5.85 to 8.8 GHz for the MIMO antenna with single ground plane. After introducing the DGS, it is found that the antenna has 10 dB return loss over an extended band from 4.4 GHz to 9.57 GHz, thus providing a bandwidth enhancement of 75%.Simulated results of S_{21} and S_{12} are shown in Fig.5.4(b). It is observed that isolation has increased after incorporating the hexagonal DGS. S_{21} is less than -15 dB throughout the operating band of the antenna system and also a maximum isolation of more than 25 dB is achieved.

5.4.1 Parametric Study:

The isolation and bandwidth behavior of the MIMO antenna with DGS is studied by varying one of the design parameters.

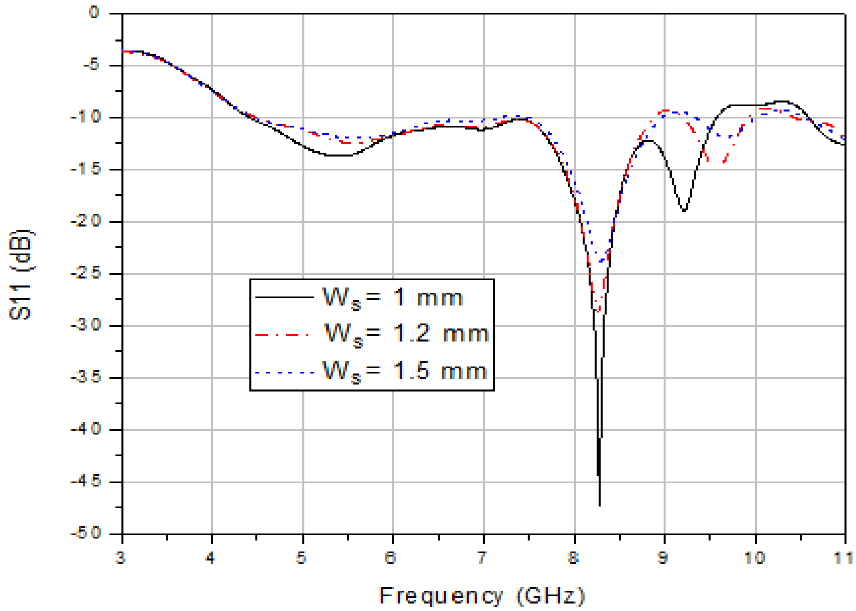


Fig.5.5. Width W_S variation against S_{11}.

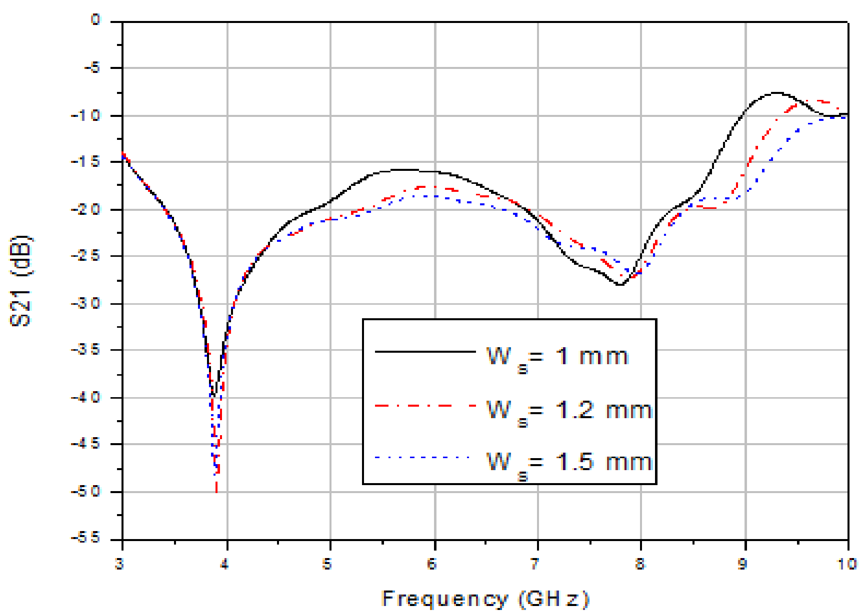
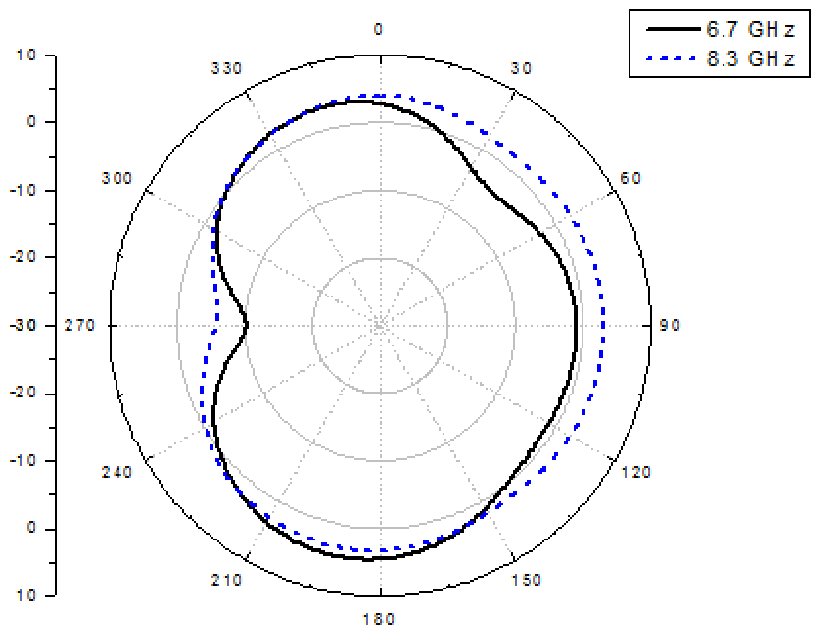


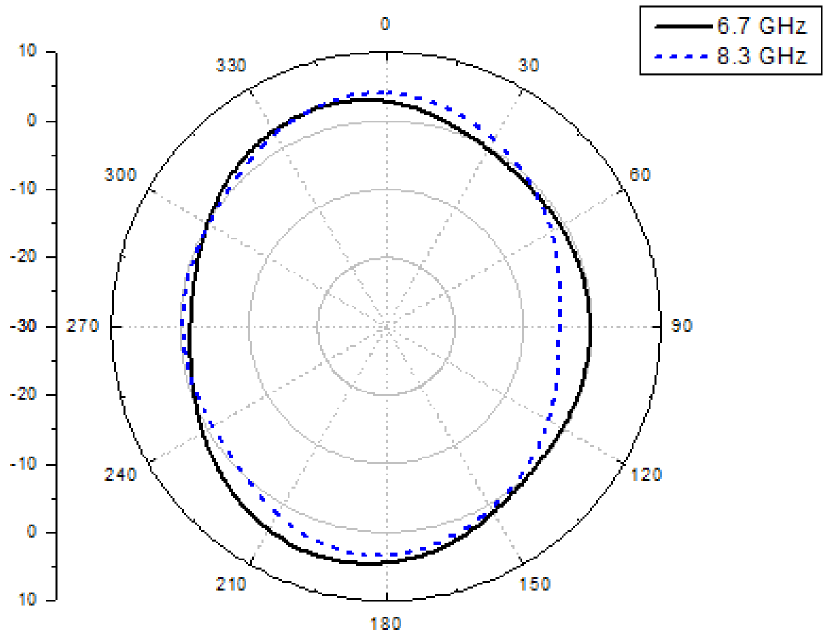
Fig.5.6 Width W_S variation against $S_{21.}$

The isolation and bandwidth behavior of the MIMO antenna with DGS is studied by varying one of the design parameters. Fig.5.5 shows the variation of return loss obtained by varying the width of the slot W_s of the hexagonal DGS from 1mm to 1.5 mm. It is apparent that a wider bandwidth is achieved corresponding to a narrow width, W_s= 1 mm. But, on the contrary, isolation increases when W_s is varied from 1 mm to 1.5 mm as shown in Fig.5.6. Hence better isolation performance corresponds to a wider slot of width 1.5 mm. High isolation of more than 20 dB is achieved in this case.

5.4.2 Radiation Performance:



(a)



(b)

Fig.5.7 Simulated radiation patterns: (a) y-z plane, (b) x-z plane.

Radiation patterns of the antenna system are obtained when only one of the ports is excited, while the other is terminated with a 50-Ω load. When one port is excited, the flow of current from the antenna through the ground plane to the other element will be obstructed by the defected ground structure. The same effect is achieved when the other port alone is excited. Simulated radiation patterns are shown in Fig.5.7, for frequencies of 6.7 GHz and 8.3 GHz in the y-z (ϕ= 90^0) and x-z (ϕ= 0^0) planes. The antenna exhibits a stable radiation behavior across the required operating band.

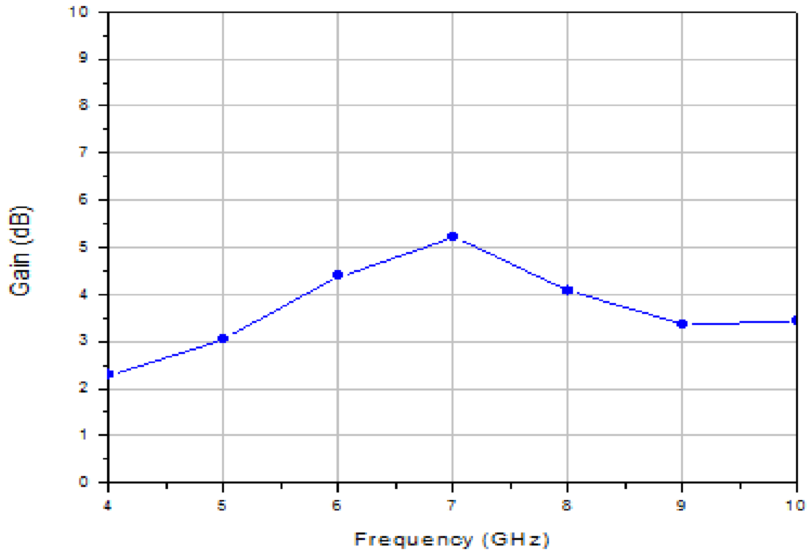


Fig. 5.8 Antenna Gain

Simulated results of antenna gain are shown in Fig.5.8 and the variation of antenna gain was found to be 3 dB across the band.

Chapter 6

Conclusion and Future Work

6.1 Conclusion:

This thesis presented the work on the analysis and design of two-element UWB MIMO antennas taking into consideration of two major performance characteristics, viz. isolation and bandwidth. Two antenna designs were proposed and discussed which satisfy the required isolation and bandwidth requirements.

A novel compact UWB MIMO antenna system with high isolation has been proposed and investigated as discussed in Chapter 4. Good isolation performance was achieved through the proposed fork-shaped structure. Isolation was found to be better than -17 dB throughout the UWB. The bandwidth of the proposed antenna covers almost the entire UWB from 4.4 to 10.7 GHz. The obtained results of isolation and bandwidth characteristics show that the proposed MIMO antenna system can work well in extremely wideband range and it is found suitable for application in UWB portable devices.

The proposed antenna system presented in Chapter 5 shows good MIMO/ diversity performance by achieving isolation of – 20 dB, facilitated through a hexagonal shaped DGS. Bandwidth also is enhanced by the DGS so as to have an operating frequency range from 4.4 GHz to 9.57 GHz, which covers almost the entire UWB (3.1 – 10.6 GHz band). Hence wideband isolation is achieved in the proposed compact antenna system with DGS and it is found suitable for portable MIMO applications.

The performed simulation results and investigations proved sufficient port-to-port isolation in the UWB and the designed antenna systems can be used, where high data rate and support for MIMO transmission is required.

6.2 Guidelines for Future Work:

- Envelope correlation coefficient can be calculated for the proposed antenna systems and the designs can be further optimized to obtain correlation coefficient of less than 0.01 across the entire UWB for good diversity performance.

- The two radiators were of similar structure and orientation. Different orientations can be tried to further reduce the mutual coupling.

- The proposed antennas have an operating bandwidth in the entire UWB. More complex isolation structures can be implemented if UWB is not a major concern, for example Bluetooth applications.

- This work can be extended to four-element MIMO antenna systems for increased channel capacity in high data-rate applications.

- Analysis of isolation becomes difficult when the number of radiating elements in a MIMO system increases. Hence simple isolation mechanisms like neutralization-line techniques can be introduced.

- Reconfigurable antenna elements can be used to enhance diversity performance.

- Time Domain characterization of the proposed antennas can be carried out in order to get physical insight on their functioning.

Publications

- Manuel Prasanna.K and S.K. Behera, "**Compact Two-Port UWB MIMO Antenna System With High Isolation Using a Fork-Shaped Structure**", *IEEE International Conference on Communication and Signal Processing* (ICCSP), Melmaruvathur, India, April 3-5, 2013.

- Manuel Prasanna.K and S.K. Behera, "**A Hexagonal MIMO Antenna System With Defected Ground Structure to Enhance Bandwidth and Isolation**", *IEEE International Conference on Communication and Signal Processing* (ICCSP), Melmaruvathur, India, April 3-5, 2013.

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